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Improving Soybean Production Using Light Supplementation at Field-Scale: A Case Study

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Abstract

In modern agriculture, there is a growing need for increasing crop efficiency while minimizing environmental impacts. The use of high-efficiency light supplementation to enhance plant development is limited for high-productive crops at field conditions (outdoor). This study evaluated the soybean plant’s yield responses in an open commercial area (field scale) cultivated under conditions of artificial light supplementation. A commercial irrigated (pivot) area received an illumination system for light supplementation (LS) in its inner pivot spans. About 40 hours of LS were applied to the plants during the soybean crop cycle. The area’s outer pivot spans did not receive light supplementation (nLS). The internode number, the plant height, the pods per plant were evaluated weekly to compute the area under the progress curve (AUPC). The grain yield at harvest was also assessed. The AUPC of the internode number, plant height and pods per plant were positively affected by the LS treatment. The regular soybean cycle (nLS) is about 17 weeks; however, the LS harvest occurred three weeks later. Light supplementation increased soybean grain yield by 57.3% and profitability by 180% when compared to nLS. Although light supplementation at field scale poses a challenge, it is now affordable since sustainable field resistant technologies are now available. The present study is the first known report of light supplementation used to improve soybean crop production at field scale.

Keywords: *Glycine max*, light-emitting diode, crop yield, crop management, agriculture 4.0

1. Introduction

Modern agriculture has been continuously compelled to advance and to make use of sustainable technologies. Such technologies include genetic breeding tools, efficient-release fertilizers, soil management strategies, intelligent use of water and agrochemicals, internet of things, crop and weather monitoring, nanotechnology and integrated techniques of farm administration among others (Ali et al., 2018; Chowdhury et al., 2019; Leakey et al., 2019; Lowenberg-DeBoer & Erickson 2019; Pandey et al., 2019; Saiz-Rubio & Rovira-Más, 2020; Singh & Singh, 2020; Devlet, 2021).

Crop producers also desire crop cultivars with the following traits: (i) optimum nutritional content for human consumption, (ii) high performance when compared to other cropping systems, and (iii) can withstand diverse environmental conditions (Roberts & Mattoo, 2019). Other currently implemented technologies include genetically modified (GM) plants that beneficial to growers, consumers, and countries’ economies (Raman, 2017) and bioactive compounds like plant growth regulators (Small & Degenhardt, 2018; Harsimrat & Kaur, 2020). Such plant growth regulators (e.g. plant hormones), when applied in small quantities, can alter plant processes from seed germination to plant senescence. Bioactive compounds can also enhance or stimulate natural plant development and the source-sink relationship of a plant’s photoassimilates (Toungos, 2018).

In the past decades, the above mentioned technologies were all used to accelerate crop intensification. The utilization levels of these technologies in Latin America and Asia countries almost matched that of North America and Europe (Pellegrini & Fernández, 2018). Additionally, a constantly growing human population and climatic changes (global warming) posed a challenge for all human activities, especially to crop production (Besada & Sewankambo, 2010; IPCC, 2014; Tamiru & Fekadu, 2019). There was also an increase in agrarian pressure on existing environmental resources (Balogh & Jámbor, 2020). Therefore, there was an actual need for crop production intensification using advanced sustainable technological approaches.

Improving plant efficiency is a process used to sustainably increase the crop production potential (Orr et al., 2017; van Iersel, 2017; Nowicka et al., 2018; Kaiser et al., 2019; Batista-Silva et al., 2020; Singer et al., 2020). This can be done using different strategies including genetic techniques like the use of genetically modified organisms (Simkin et al., 2019), management of soil microbiota (Silva et al., 2021), or the addition of yield factors such as light (Goto, 2003; Gupta, 2017).

Gomez and Izzo's (2018) review illustrated the positive effects of light supplementation using light-emitting diode (LED) on plant metabolism and the negative impact of pest insects and diseases on crop production. Therefore, crop producers can optimize energy efficiency and plant productivity by increasing the canopy light capture efficiency and controlling the light output in response to environmental and physiological parameters using LEDs (Hemming, 2011; Bures et al., 2018).

Global food production relies on plant protein production for stock-farming and subsequent human consumption. The soybean is considered a strategic crop for plant protein production. Brazil is a leading soybean producer with an annual grain production of 124.8 million tons (Conab, 2020). Brazil's high soybean production results from a combination of factors such as the use genetically improved cultivars and advanced crop management technologies. Because sufficient amounts of food must be produced to meet the needs of an increasing population in a climate-changing world, newer techniques and advanced farm management strategies with minimal environmental impact must be implemented to increase crop production.

The objective of this study was to evaluate the soybean plant and its yield responses in a commercial area (field scale) where it was cultivated in conditions of artificial light supplementation.

2. Method

2.1 Experimental Area and Soybean Cropping

The experiment was implemented on a commercial farm in Monte Carmelo, Minas Gerais state, Brazil; located at 18°57″ S, 47°25″ W, at 980 m above sea level that used irrigation (pivot system). The region's most common and representative biome is the Cerrado (Savannah-like biome). The climate of the region is Cw (humid subtropical with dry winter) (Beck et al., 2018).

The soil's physical analysis (0-0.4 m) indicated 450, 100, and 450 g kg^{-1} of sand, silt, and clay, respectively. The soil chemical characteristics up to a depth of 0.4 m are presented in Table 1.

Table 1. Soil chemical characterization at 0-0.2 and 0.2-0.4 m soil layer.

pH H_2O	Ca	Mg	Al	H+Al	CEC	V	P	K	S.O.M
1-2.5	------------------$\text{cmol}_c\ \text{dm}^{-3}$------------------					%	------mg dm^{-3}------		g kg^{-1}
--------------------------------------0-0.2 m soil depth--------------------------------------									
6.9	6.03	2.87	0	1.26	10.44	88	188	96	2.9
-------------------------------------0.2-0.4 m soil depth-------------------------------------									

6.8	5.70	2.78	0	1.08	9.77	89	158	82	2.3

B	Co	Cu	Fe	Mn	Mo	Si	Zn
----------mg dm^{-3}----------							
----------0-0.2 m soil depth----------							
0.19	1.7	9.0	14.0	1.9	2.9	12.4	12.8
----------0.2-0.4 m soil depth----------							
0.14	1.3	7.7	17.0	3.5	2.3	11.4	11.1

CEC = cation exchange capacity at pH 7; V = saturation of bases; S.O.M. = soil organic matter. Methodologies source: Embrapa (2017).

Despite having a large proportion of clay in the soil and a high natural fertility, 3,000 kg ha^{-1} of soil remineralizer (rock powdery) (FMX® Tratto. Aparecida de Goiânia, Brazil) was applied to the entire experimental area 30 days before sowing the soybean; 400 kg ha^{-1} of organomineral 06-30-05 (% of N, P_2O_5, K_2O) (Valoriza Agro Ltda. Patos de Minas, Brazil) and 150 kg of KCl was applied at the time of sowing, and 2 L ha^{-1} of Mn was sprayed on the plant canopy 40 days after crop emergence.

The soybean cultivar evaluated in this experiment was the Desafio 8473 RSF (Brasmax® GDM. Cambé, Brazil) – indeterminate growth, maturity group 7.4. In October 2019, fourteen seeds were sown per square meter (280,000 plants per hectare); the plants were then harvested in February 2020. The daily average air temperature during the experimental period ranged from 24 to 34 °C (weatherspark.com).

At the experimental area, insect pests, plant diseases, and weeds were controlled using soybean-registered products as per manufacturer's indications. All areas were monitored before and after first application and products reapplied as needed. The crop managements and water irrigation were also similar between the light-supplemented and the no-light-supplemented treatments.

2.2 Treatments and Experimental Investigation

The pivot where the present study was implemented has ten spams and a radius of about 571 meters. In the four internal pivot spams (33.5 ha), a light supplementation system including full-spectrum light-emitting diode (LED) boards were installed. The main RGB spectral bands were about 59% red, 33% green and 8% blue. A continuous light range of approximately 40 m wide by 230 m long was projected below the extension of the four internal pivot spams.

Each LED board has a power varying between 50 and 200 watts (W). About 600 W h^{-1} ha^{-1} were consumed during the light supplementation process. The LED boards were positioned about 3 meters above the plant canopy and distributed to ensure equally distributed light power regardless of the different moving speeds of the various pivot spams. The luminous flux per unit area (lux) at the soybean canopy level was about 30 lx. The light system used to supplement the soybean crop is presented in Figure 1.

Figure 1. Light and water irrigation system (A) used to light-supplement soybean crop at night (B) and very cloud days

The light system was turned on every night (after complete sunset) and on very cloudy days. Approximately 480 hours of light supplementation was applied to the whole area during the soybean crop cycle. Since the pivot completes a full turn over the cropping area in 12.8 hours (a circular routine), each plant received about 40 hours of light supplementation during its cycle.

The light supplementation started at the V3-V4 (third-fourth trifoliate leaf fully expanded) and ended at the R5-R6 (beginning-full seed) soybean phenological stage. The six external pivot spams (69.5 ha) received no light supplementation.

Between the first and second pivot towers (second spam), a homogeneous area of 50 by 40 m (2,000 m^2) was delimited to be evaluated as the “light-supplemented” (LS) treatment. Between the eighth and ninth pivot tower (ninth spam), a homogeneous area of 50 by 40 m (2,000 m^2) was delimited to be evaluated as the “no-light-supplemented” (nLS) treatment. The experimental sketch of the pivot is presented in Figure 2.

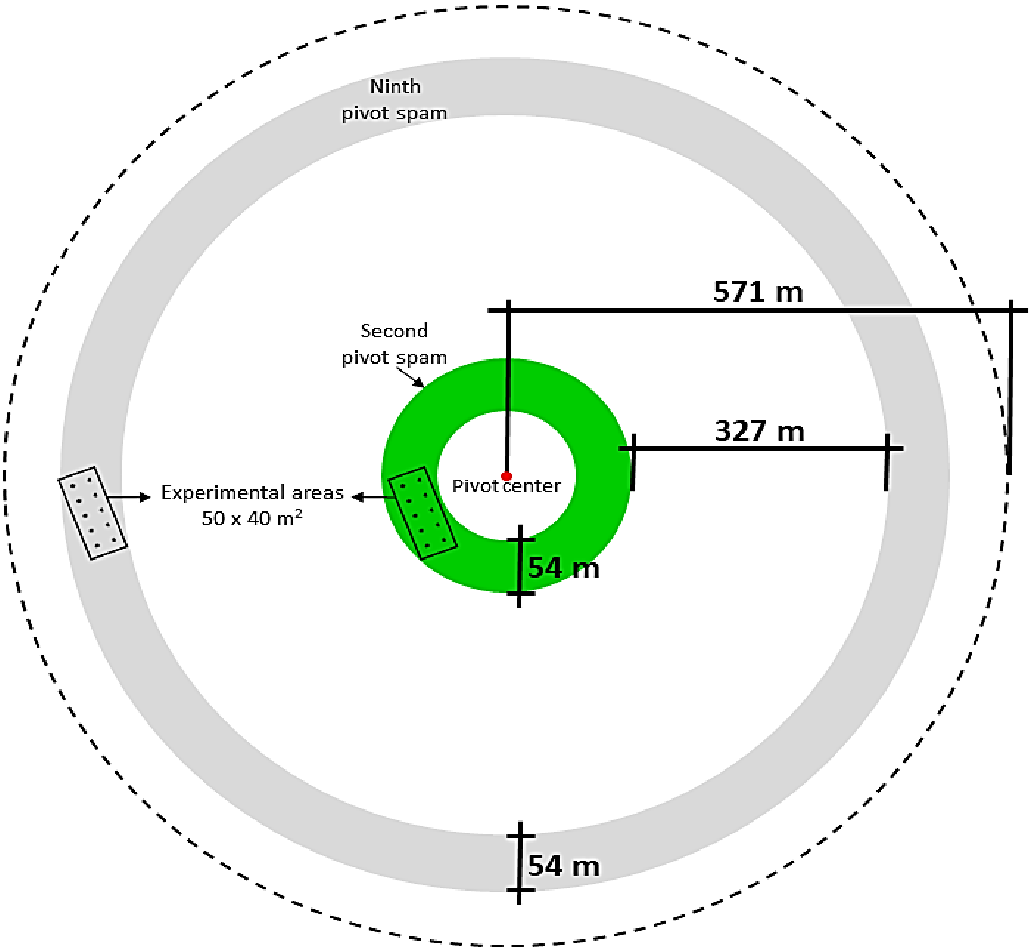


Figure 2. Experimental sketch of the irrigation pivot (102 hectares) to evaluate the effects of light supplementation on soybean crop development. Green pivot spam received light supplementation. Rectangles indicate the position of both treatments, with and without light supplementation, and dots in each rectangle indicate sampling points.

2.3 Soybean Evaluations

The evaluations of the internode, plant height (from soil level to the highest leaflet node), and pods per plant were done weekly from R3 (beginning pod) to R7 (beginning maturity) soybean phenological stage. During these nine weeks, evaluations were done once each week; no further assessments were possible after R7 because the plants in the nLS treatment attained physiological maturity earlier than the plants in the LS treatment. The average measurement of each variable evaluated was estimated from a representative assessment of plants at 10 sampling points in each area (2,000 m^2) with each sampling point evaluated considered a replication.

The influence of LS or nLS on each variable was evaluated using the area under the progress curve (AUPC) of each variable (Van der Plank, 1963; Simko & Piepho, 2012). The AUPC was calculated by the trapezoidal integration: $AUPC = \Sigma(dti \times ((Yi + Yi{+}d)/2))$, where dti is the time interval between every two observations of Yi and $Yi{+}d$. The area under the progress curve (AUPC) of the variables was calculated based on nine evaluations. Correlations between the AUPC of the variables evaluated were computed to determine if there was a linear relationship between them (Pearson, 1892).

The areas used for each treatment (2,000 m^2), were harvested at 115 and 136 days after sowing for the nSL and SL, respectively. The grain productivity in each area was expressed in kg ha^{-1}.

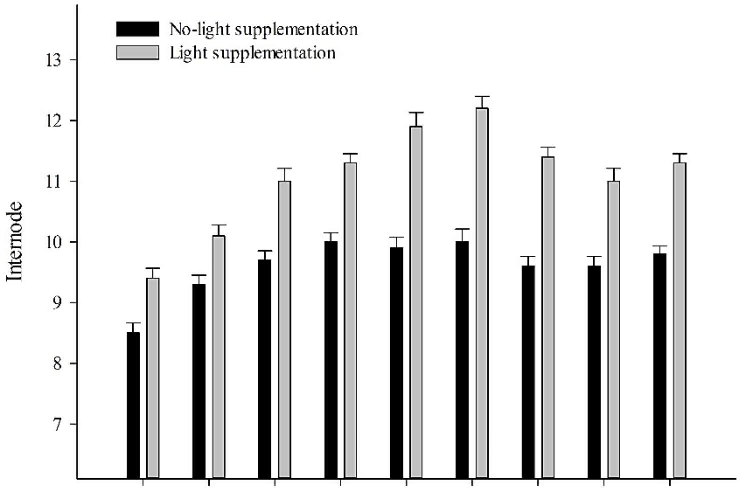
2.4 Statistical Analysis

Extreme values (outliers) in the AUPC of each variable were identified using boxplot graphs of the residues (Chambers et al., 1983). When outliers were identified, the outlier was replaced using a mean value of the data set that did not include the outlier value (Burke, 2001; Kwak & Kim, 2017). The boxplots were generated using SPSS Statistics® software, which was also used to calculate the Pearson’s correlation coefficients and the basic assumptions for the analysis of variance (normality of residue distribution by Shapiro-Wilk and homogeneity of variances by Levene, both at $p > 0.01$).

The analysis of variance (ANOVA, F test) was performed after confirming its assumptions and considering a fully randomized experimental design. When significant differences were observed ($p < 0,05$) in ANOVA, the AUPC of the internode number, plant height, and pods per plant were compared using Tukey’s test of averages ($p < 0.05$) to distinct the treatments (LS and nLS). The ANOVA and Tukey’s test analyses were performed using SISVAR® statistical program. Sigma Plot® v.12 software was used to generate the graphics.

3. Results

The data from the weekly evaluations of all variables (soybean internode number, the plant height, and the number of pods per soybean plant) for both treatments (LS and nLS) did not include any outliers based on the boxplots of all variables and treatments. This observation indicated that the responses were clustered around a mean with low standard error. The soybean variables and their respective standard errors during the nine weeks are presented in Figure 3.



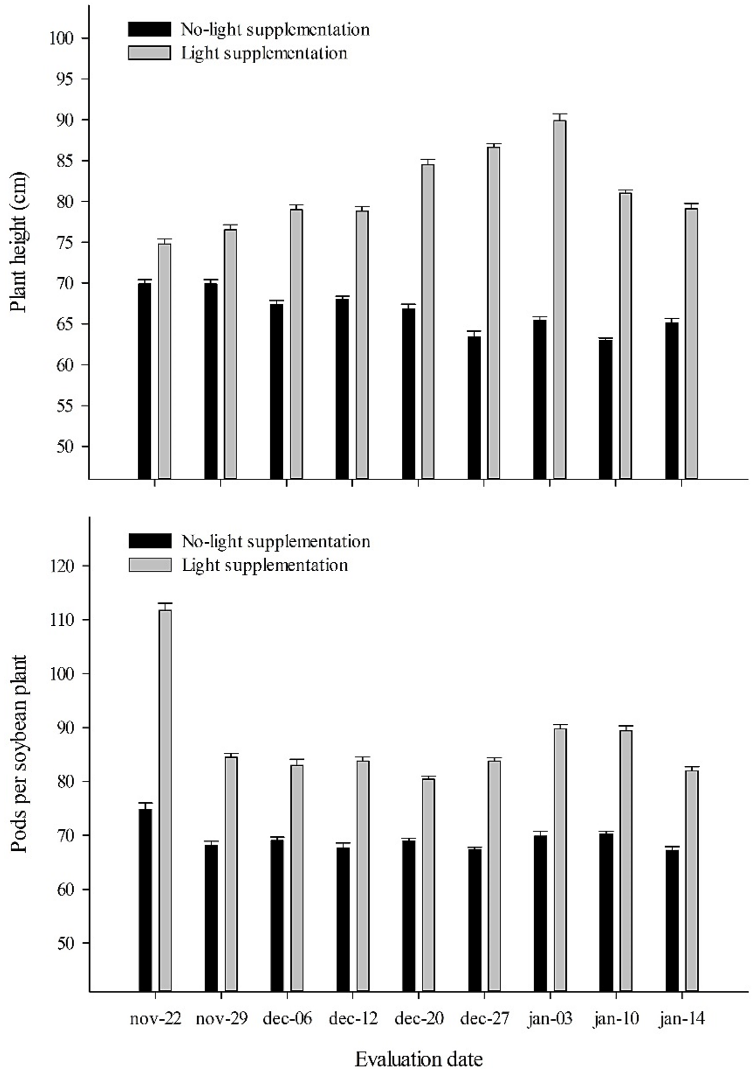


Figure 3. Internodes, height and pods per soybean plant (cultivar Desafio 8473 RSF - Brasmax®) under light supplementation and no-light supplementation. Lines over bars indicate standard error

The number of internodes per soybean plant, the plant height, and the number of pods per plant of the LS treatment were higher when compared to the no-light supplementation. These superior plant responses of the LS treatment can also be observed in Figure 4.

Figure 4. Soybean plants at 80 days after sown from the light supplementation (left, R5.3 soybean phenological stage) and no-light supplementation treatments (right, R6-7 soybean phenological stage). Each blue stretch in the metric tape = 0.1 m

The analysis of variance of the AUPC and the presumptions (normality and homogeneity) are presented in Table 2.

Table 2. Analysis of variance (F test) and statistics of assumptions of the area under the progress curve of the variables soybean internode number, the plant height and the number of pods per soybean plant

SV	DF	Internodes	Height	Pods per plant
Light supplementation	1	375**	1,590**	2,649**
Error	18			
CV (%)		1.67	1.17	0.98
KS	20	0.935^{+}	0.985^{+}	0.964^{+}
L	1+18	1.139^{+}	0.106^{+}	0.262^{+}

**: significant differences at 0.01. CV (%): coefficient of variation. KS: Kolmogorov-Smirnov's statistics for normality of the residue distribution ($p > 0.01$). L: Levene's statistics for homogeneity of the data variances ($p > 0.01$). $^{+}$: normality of residues (KS) or homogeneity of variances (L) fulfill.

All the AUPC data of the soybean variables (internode number, plant height, and pods per plant) met the ANOVA presumptions (normality of the residue distribution and homogeneity of the variances). Also, the coefficients of variation, CV (%), were very low (< 2%). Thus, it was suitable to proceed with the ANOVA, which indicated significant differences ($p < 0.01$) between the treatments (LS and nLS).

The AUPC of the internodes per soybean plant, the plant height, and the number pods per plant of the LS treatment were 15.6, 23.3, and 25.3% superior to that of the nLS treatment.

The Pearson's correlation computation and interpretation require that the data be normally distributed and with no outliers (extreme values) (Figueiredo Filho & Silva Jr., 2009); these requirements were met (Table 1). All the correlations observed (Table 3) were strong correlations ($r > 0.9$) according to Callegari-Jacques (2003) and attained statistical significance ($p < 0.01$).

Table 3. Pearson's correlation (*r*) between the AUPC of the variables studied

	Internodes	Plant height	Pods per plant
Internodes	1	0.962**	0.970**
Plant height		1	0.990**
Pods per plant			1

Internodes: soybean internode number; Plant height: soybean plant height; Pods per plant: number of pods per soybean plant. **: significant differences at 0.01.

The soybean cultivar evaluated has a cycle of approximately 17 weeks. At day 115 after sowing, the soybean plants from the nLS area (2,000 m^2) were harvested; however, the harvest in the LS area was done three weeks later representing a 17.6% longer growth cycle.

The estimated productivity of the nLS was about 4,500 kg ha^{-1} (75 bags ha^{-1}; 1 bag = 60 kg), while the LS treatment was about 7,080 kg ha^{-1} (118 bags ha^{-1}). The LS grain productivity was 57.3% higher were light supplementation was applied, and 109.5% above the average of the Brazilian soybean productivity (3,379 kg ha^{-1}) (Conab, 2020).

The average cost to produce the soybean from soil management until harvest is about 55 soybean bags per hectare. The average cost required by the light supplementation was about seven (7) bags ha^{-1}. Thus, the profitability of the soybean traditionally produced (nLS) and the soybean produced with light supplementation were about 20 and 56 bags ha^{-1}, respectively.

4. Discussion

Soybean development and flowering are majorly influenced by environmental factors such as photoperiod and temperature (Kantolic, & Slafer, 2007; Wu et al., 2015). The extension of the soybean crop cycle by three weeks due to light supplementation also increased the plant's photosynthetic activity period. This extended cycle increased the biomass accumulation via natural daily photosynthesis; a process absent in the regular cycle of the soybean cultivar (17 weeks) where light is not supplemented. This conjunction of factors resulted in taller soybean plants, more internodes, more pods, and, consequently, over 57% further grain productivity.

Crop cycle extension, the number of nodes, pods, and seeds per pod, and the pod distribution within the soybean canopy are affected by extended photoperiods (Kantolic, & Slafer, 2007; Kantolic, & Slafer, 2001; Kantolic, & Slafer, 2005; Kantolic et al., 2013; Nico et al., 2016). The photoperiod regulation process results in changes to the soybean development, such as the number of pods and seeds established per unit land area (Kantolic et al., 2013).

In this study, the extra yield (57.3%) generated by an additional photosynthesis cannot solely be attributed to the hours of light supplementation provided to each soybean crop (about 40 hours). Other hypotheses should be considered; for example, photomorphogenesis (light-mediated development of the plant morphology) (Beyi, 2018; Tripathi et al., 2019), uperregulation or downregulation of phytohormones and phytochromes (Lymperopoulos et al., 2018; Tripathi et al., 2019; Faizan et al., 2020), and changes to the secondary plant metabolism (Ouzounis et al., 2015; Thoma et al., 2020).

Crop inputs, such as fertilizers, plant inoculants, and phytosanitary products, applied during the crop cycle are solely intended to maximize crop production and economic returns. Although such inputs have adverse effects on soil dynamics, these effects are often neglected (Bitew & Alemayehu, 2017). However, the light supplementation for field crops has the potential to reduce these inputs, especially fertilizers.

The fertilizer efficiency in this study probably resulted from the significant increase in the shoots' biomass following light supplementation. An increase in the shoot biomas in turn cause a proportional increase in the root biomass. This improved root development increases the efficiency of the root nutrient absorption, thus, increasing the fertilizer efficiency (Fageria & Moreira, 2011).

Crop production has always been intrinsically correlated nutritional, microbiological, environmental, and economic aspects that interact in a spatially sensitive manner (Joglekar et al., 2019). Consequently, response models are used to understand the consequences of such elements and their interactions. Such models can integrate valuable information about physiological processes, sowing time, irrigation blade, fertilizer doses, management of insect pests and plant diseases, and their impacts on the soil-crop-environment relationships (Sihag & Prakash, 2019). Additionally, including climate information in such models can shed light on the relationship between crop production and weather oscillations and which in turn can be used to enhance the resilience of the global food system (food security) to unexpected climate-related shocks (Tamiru & Fekadu, 2019; Mulungu & Ng'Ombe, 2019; Patle et al., 2020; Heino et al., 2020).

Currently, there is an ongoing rapid increase in digitalization and integration of technologies in agriculture that is aligned with the sustainability of the ecosystems to enhance. These changes are likely to propel modern cropping to a higher level of productivity (Agriculture 5.0) (Saiz-Rubio & Rovira-Más, 2020).

Before design cropping factors such as the genetic material to be sown, several factors should be availed. These factors include the phytosanitary management and the level of technology implemented other primary factors such as the nutrient availability, water supply, and light (usually from a natural source). Although availing light supplementation at the field scale is challenging to control, with affordable technologies and field resistant hardware light supplementation for crop production is possible for large commercial areas.

Currently, the world's population is about 7.88 billion people (Worldometers.org, 2021). Intensifying crop production can supply the food required by this population now and in the future. However, this does not necessarily imply hunger alleviation. Losses in crop production must also be reduced and income equity sought concurrent with the improvements in the cropping production systems (Tilman et al., 2011; Pellegrini & Fernández, 2018).

The light supplementation technology also has a great potential to diminish the deforestation of new native areas for the purposes of crop production (Byerlee et al., 2014; Phalan et al., 2016; Koch et al., 2019). Although crop productivity can be increased with an appropriate implementation of light supplementation throughout the crop cycle, little is known about the interactions among different factors (e.g., soil, plant, climate, management), crop performance, the yield construction, and the cost-benefit relationships.

The crop production costs generated by the light supplementation system is dependent on various factors. These factors include the efficiency of the structure available (e.g., machinery, farm administration), the technology implemented (e.g., genetic materials, fertilizers) and the use precise agricultural systems (Boehlje, 2021). Other factors include irrigation system characteristics (e.g., pivot height which affects light dissipation, light supplementation on static irrigation areas), soil structuring (e.g., no physical or chemical limitation, healthy microbiota), energy supply (e.g., wiring, constancy and stability) and internet of things and crop management. Thus, the cost and profitability in the present study reflects a specific scenario of soybean production that may vary on a case to case basis. Despite this observation, light supplementation presents an opportunity to improve crop production in the same area.

There are ongoing research studies on light supplementation at field scale on many crop species with promising results. For example, researchers have observed a reduced occurrence of leaf diseases and pest insects together with an increased weed infestation in light-supplemented areas. However, focused studies are yet to confirm and understand such responses. Based on an extensive literature research, this is the first known report of light supplementation using full-spectrum LED lights to improve soybean crop production at field scale.

5. Conclusions

About 40 hours of light supplementation are required per plant during its crop cycle to positively affect its number of internodes, pods, plant height, and crop cycle.

Light supplementation increased soybean grain yield by 57.3% and its profitability by 180% compared to cultivation processes without artificial light supplementation.

Light supplementation to plants at field scale is a feasible and promising technique to sustainably improve crop production in the same agricultural area they are currently grown.

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