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THERMAL REQUIREMENTS AND AGROMETEOROLOGICAL MODELING OF COTTON GROWTH UNDER SOIL FERTILITY LEVELS

EXIGÊNCIAS TÉRMICAS E MODELAGEM AGROMETEOROLÓGICA DO CRESCIMENTO DO ALGODOEIRO SOB NÍVEIS DE FERTILIDADE DO SOLO

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ABSTRACT: The objective was to quantify the thermal requirements and model the growth of cotton as a function of air temperature and degree-days, under levels of soil saturation and potassium fertilization, grown in a protected environment, in Bom Jesus, Piauí. The experimental design used was a completely randomized design (DIC) with a 3 X 3 + Witness factorial scheme, consisting of three levels of base saturation (V%) (50%, 60% and 70%) and three concentrations of potassium fertilization doses (50% below recommended; recommended, according to soil analysis; 50% above recommended) and Control, without K application, with four replications. Plant height, stem diameter, number of nodes, midrib length and leaf area were evaluated. The meteorological data were obtained in a portable meteorological station, installed inside the protected environment. Among the stages, the First Boll-Harvestpresented the highest thermal demand, with an average of 551.7 °gd and 34 days of duration, followed by the Emergence-First Floral Bud (435.6 °gd), First Floral Bud- First Flower (362.5 °gd) and First Flower-First Boll (300.3 °gd), the Sowing-Emergence phase obtained 51.4 °gd. Air temperature is the meteorological element with the greatest impact on cotton development.

Keywords: Phenology, Graus-dia, *Gossypium hirsutum*L.

RESUMO: Objetivou-se quantificar as exigências térmicas e realizar a modelagem do crescimento do algodoeiro em função da temperatura do ar e graus-dia, sob níveis de saturação por base do solo e de adubação potássica, cultivado em ambiente protegido, em Bom Jesus, Piauí. O delineamento experimental utilizado foi o inteiramente casualizado (DIC) com esquema fatorial 3 X 3 + Testemunha, constituído por três níveis de saturação por bases (V%) (50%, 60% e 70%) e três concentrações doses de adubação potássica (50% abaixo da recomendada; recomendada, de acordo com a análise do solo; 50% acima da recomendada) e Testemunha, sem aplicação de K, com quatro repetições. Avaliou-se a altura de planta, diâmetro caulinar, número de nós, comprimento da nervura central e área foliar. Os dados meteorológicos foram obtidos em uma estação meteorológica portátil, instalada no interior do ambiente protegido. Dentre os estádios, o Primeiro Capulho-Colheita foi o que apresentou maior exigência térmica, com em média 551,7 °gd e 34 dias de duração, seguido pelo Emergência-Primeiro Botão Floral (435,6 °gd), Primeiro Botão Floral-Primeira Flor (362,5 °gd) e Primeira Flor-Primeiro-Capulho (300,3 °gd), a fase de Semeadura-Emergência obteve 51,4 °gd. A temperatura do ar é o elemento meteorológico de maior impacto no desenvolvimento do algodoeiro.

Palavras-chave: Fenologia, Graus-dia, *Gossypium hirsutum*.

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INTRODUCTION

Cotton farming is one of the most economically important agricultural activities for Brazilian agribusiness (CARDOSO et al., 2010). Cotton (*Gossypium hirsutum L.*) stands out as one of the most important agricultural commodities sold in the foreign market, being the indispensable raw material for the textile industry (FERREIRA FILHO et al., 2009). According to ABRAPA (2019), Brazilian cotton production in the 2018/19 harvest was 6,945.1 thousand tons, with a planted area of 1,618.6 thousand hectares.

In the Cerrado, most soils do not have sufficient nutrient reserves to supply the amounts extracted by crops and exported at harvest, and supply from fertilization is essential. Correction of soil acidity and mineral fertilization have progressively increased the cost of cotton production, reaching values in the order of 20% to 30% of the total cost of crop management, and this reality is quite different from world production, which is of approximately 14% (CARVALHO et al., 2011).

Allied to this, the climate, despite recent technological and scientific advances, remains an important variable in agricultural production, due to the influences it exerts on the different segments of the production chains of the agro-industrial complex in any country in the world.

In cotton, the ideal air temperature range for its best performance is between 20 and 30 °C, however, it tolerates variation between 18 and 40 °C (REDDY et al., 1991) with a basal temperature lower than 15 °C (CHIAVEGATO et al., 2009). Despite this behavior, this crop is sensitive to the action of this climatic element, which significantly interferes in its phenology, leaf expansion, biomass production, among other aspects (CHIAVEGATO et al., 2009).

Associated with the effect of this meteorological element, there are the thermal units or degree-days. In this method of analysis, a minimum temperature is considered below which the plant stops its development (lower base temperature), with the degree-day defined as "the amount of heat effectively accumulated during the day and favorable to plant growth" (PEREIRA et al., 2002).

The characterization of its thermal requirements, both total and for each phenological phase, is crucial to predict the duration of the crop cycle as a function of the environment. This information, associated with the knowledge of the phenology of the crop, can be used in planning to define the sowing time, the use of inputs and the harvest time (SCHAFER, 2009).

Given the importance of studying agrometeorological conditioning in agricultural crops, the objective was to quantify the thermal requirements, as well as to model the growth of cotton as a function of air temperature and degree-days, under saturation levels by soil and soil base. of potassium fertilization, cultivated in a protected environment, in Bom Jesus, Piauí.

MATERIAL AND METHODS

The experiment was carried out in a protected environment (screened) using shade net with 50% shading, with an area of 50 m^2 and a ceiling height of 4 meters, at the Federal University of Piauí (UFPI), Campus ProfessoraCinobelinaElvas, in Bom Jesus – PI, between August and November 2019. The municipality is part of the semi-arid region of Piauí, with a hot and humid climate, classified by Köppen as Awa (rainy tropical with dry season in winter and average temperature of the hottest month above at 22 °C) (ALVARES et al., 2013). Located at geographic coordinates 09º04'28"S, 44º21'31"W, and average altitude of 277 m, with average precipitation between 900 and 1200 mm $year^{-1}$ and average temperature of 26.2 °C (INMET, 2019).

The soil used was a medium texture Yellow Latosol, from the municipality of Monte Alegre, PI. Chemical analyzes were carried out at the UFPI Soil Analysis Laboratory, whose characteristics are shown in Table 1.

Table 1. Chemical analysis of the soil used in the experiment. UFPI/CPCE, Bom Jesus, PI. 2017.

Ph	P	K	K	Ca	Mg	Al	H + Al	V	MO
(H_2O)	------- mg dm^{-3}------		------------------------- $cmol_c dm^{-3}$ ------------------------					%	g kg^{-1}
5.4	85.24	69.40	0.18	1.98	0.69	0.00	2.64	50.00	13.2

The effects of the factors Saturation by bases were analyzed, whose source was dolomitic limestone (PRNT 100) and K dose, using Potassium Chloride (KCl) as a source, with the following guarantee: 60% of K2O, isolated and combined on the growth of the herbaceous cotton variety FM 975 WS.

The experiment was carried out using a completely randomized design (DIC) with a 3 X 4 subdivided factorial scheme (time analysis every 20 days), consisting of three liming requirements (NC) (0 ton ha^{-1}, 54.8 ton ha^{-1} and 109.6 ton ha^{-1}) based on levels of base saturation (V%) (50%; 60% and 70%, respectively) and four doses of potassium fertilization, as follows: without application of K (0 kg ha^{-1}); 50% below the recommended dose (63 kg ha^{-1}); recommended dose (126 kg ha^{-1}) and 50% above the recommended dose (190 kg ha^{-1}); with four replications, totaling 48 experimental units. Each experimental unit consisted of a plastic pot with a capacity of 20 L standardized with green color and a plant.

The FM 975 WS variety was used in the experiment, which stands out among the cotton varieties recommended for planting in the northeastern semi-arid region, is genetically modified, resistant to insects and tolerant to the herbicide glufosinate ammonium. It has a medium cycle, large bolls, with an average of 6.5 g, dryland productivity in the semi-arid region above 2.0 ton ha^{-1} of seed cotton.

Liming was carried out with dolomitic limestone (PRNT 100), at doses calculated to reach 50%, 60% and 70% base saturation (V%) (0 ton ha^{-1},54.8 ton ha^{-1} and 109.6 ton ha^{-1}, respectively). The corrected soil was kept in plastic bags for 90 days with water content at field capacity. Then, the soil was air-dried again and the base saturation analysis was performed to confirm the treatment values.
From the chemical analysis of the soil, 3.8 g dm^{-3} of phosphorus in the form of triple superphosphate (TSP) were applied to the foundation. Nitrogen fertilization was performed in topdressing in the form of urea, where 74 mg dm^{-3} were applied, divided into two applications at 20 and 40 days after sowing.

Following the recommendation of Carvalho et al. (2011), KCl doses applied on foundation and at 20 and 40 days after sowing, according to treatments: without K application – 0 mg $vase^{-1}$ (0 kg ha^{-1}); 50% below the recommended dose - 633.3 mg $vase^{-1}$ (63 kg ha^{-1}); recommended dose - 1266.6 mg $vase^{-1}$ (126 kg ha^{-1}) and 50% above the recommended dose -1900.0 mg $vase^{-1}$ (190 kg ha^{-1}).

Sowing was performed manually, distributing 6 seeds in pots, and covered with approximately 3 cm of soil, thinning was performed 7 days after seedling emergence, which occurred 5 days after sowing. On the 20th day after emergence, manual thinning was performed, leaving one plant per pot, in addition to the first topdressing fertilization with N and K.

Irrigation was performed manually daily at 4:00 pm in the same amount, equivalent to 80% of the soil's field capacity, according to the plants' water needs, as the pots were perforated and, therefore, drained naturally so as not to leave the plant enter wilting point. All phytosanitary treatments were carried out in accordance with the recommendations made by Farias (2012).

Following the recommendations of Beltrão et al. (2001), growth was evaluated at an interval of twenty days from seedling emergence, obtaining data on the following variables: plant height in cm (length from the collar to the terminal bud), stem diameter in mm (at 1 cm of soil surface), number of nodes (counting the number of nodes), leaf area from the equation proposed by Grimes and Carter (1969):

$$AF = 0.4322n^{2.3002}(cm^2) \quad (1)$$

Where: AF is the leaf area and n is the length of the main vein of each cotton leaf.

The leaf area per plant was determined by multiplying the values of the leaf area by the number of leaves of each plant.

The meteorological data were obtained in a portable meteorological station (model Aw001) that was installed in the center of the protected environment at 1.50 m from the surface. The climatic elements that were monitored: air temperature (°C), relative humidity (%), atmospheric pressure (hPa), wind speed (m s^{-1}) and precipitation (mm). All meteorological variables were collected every three hours and the diurnal (Td), nocturnal (Tn) and daily (Tm) average was calculated according to the following equations:

$$Td = \frac{T_{06:00}+T_{09:00}+T_{12:00}+T_{15:00}}{4} \quad (2)$$

$$Tn = \frac{T_{00:00}+T_{03:00}+T_{18:00}+T_{21:00}}{4} \quad (3)$$

$$Tmed = \frac{T_{00:00}+T_{03:00}+T_{06:00}+T_{09:00}+T_{12:00}+T_{15:00}+T_{18:00}+T_{21:00}}{9} \quad (4)$$

Where: Td is the average daytime air temperature, Tn is the average nighttime temperature, Tmed is the average daily temperature, and T is the hourly temperature.

The thermal accumulation (TA) of the culture was calculated based on the degree-day methodology, through Eq. 2 (PEREIRA et al., 2002), which consists of the daily thermal sum of the crop, ending with the general sum, resulting in its thermal need.

The minimum basal temperature used was 10 °C (CHIAVEGATO et al., 2009).

$$AT(°gd) = \sum_{i=1}^{n}(Tmed - T_b) \quad (5)$$

Where: AT is the thermal accumulation (°gd); Tmed is the daily average air temperature (oC); Tb is the lower base temperature (oC); n is the number of days in the analyzed period.

The analysis of variance (ANOVA) of the factors saturation by bases (V%) of the soil and potassium fertilization (K) was carried out. If there was significance, the regression analysis was carried out. In order to verify the relationship between the phytotechnical and meteorological variables, a regression analysis was carried out between the variables, using R software version 3.6.1 (R CORE TEAM, 2019). The correlation coefficients (R) of each adjustment were classified as: very strong (R≥0.90), strong (0.70≤ R<0.90), medium (0.40≤ R <0.70) and weak (R<0.40) (CHRISTMANN, 1978). A Tukey test ($p < 0.05$) was performed to analyze the thermal accumulation by phenological stage between each treatment.

RESULTS AND DISCUSSION

The average air temperature, in the analyzed period, presented a maximum of 36.3 °C, a minimum of 21.8 °C and a thermal amplitude of 14.5 °C. Regarding relative humidity, a maximum of 56.8%, a minimum of 21.7% and an amplitude of 35.1% were recorded.

Regarding the thermal requirement of the crop (degree-days), an average of 14.8 °gdwas observed, with a variation from 6.8 to 21.3 °gd (Figure 1).

In addition, wind speed ranging from 0 to 8.1 m s-1 was obtained and there was no precipitation in the analyzed period.

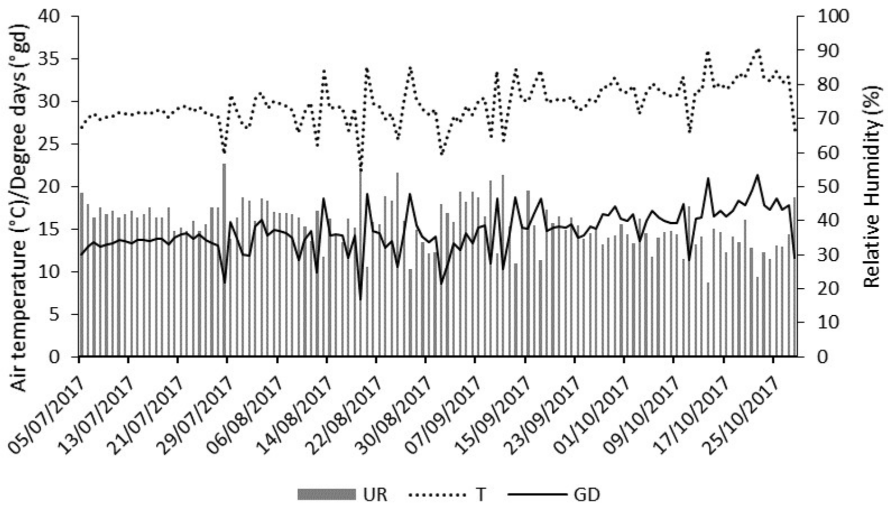

Figure 1. Temporal evolution of relative humidity (RH), average air temperature (T) and degree days (GD) in a cotton crop under protected environment, grown in the region of Bom Jesus, Piauí

The highest temperatures recorded occurred in October (Figure 1), where a greater daily thermal requirement was quantified, since these factors are closely linked and, consequently, there is a record of lower relative humidity, due to their inverse relationship proportional (VIANELLO, 2000). Milder temperatures and higher relative humidity were found in July.

As for the adaptation of the crop, it is believed that the behavior of the climatic elements did not harm the development of the cotton plant, considering that 81.9% of the air temperature records were located in the range considered optimal – 20 to 32 °C – (EMBRAPA, 2006) and, those that were not found in this, understood the tolerable limit for the same – 18 to 40 °C (REDDY et al., 1991). On the other hand, the relative humidity values were found to be lower than those recommended – around 60% (EMBRAPA, 2017). The diurnal and nocturnal temperatures in the experimental period had an adequate behavior for the development of the culture (Figure 2), within the required limits of 20 to 40 °C for daytime and 12 to 27 °C for nocturnal (EMBRAPA, 2006), the exception observed was on 10/14/2017, where 41.2 °C was recorded during the day. It is worth noting that the productivity obtained by the plants (Figure 3) is within the expected for the crop for the State of Piauí - 3413.0 kg ha^{-1} (ABRAPA, 2019), evidencing the adequate development of the crop under the climatic conditions of the region.

The highest cotton yields were observed in treatments with 70% base saturation (V%) and application of recommended K doses and 50% above the recommended (V70K2 and V70K3, respectively) (Figure 2). In treatments with the need for liming (NC) to reach base saturations of 50% and 60%, they showed similar productivity behavior in relation to K doses, with a lower value for treatments without the application of potassium fertilization, with no difference for the other doses.

This positive effect of potassium fertilization on cotton yield was also verified by Minton and Ebelhar (1991).

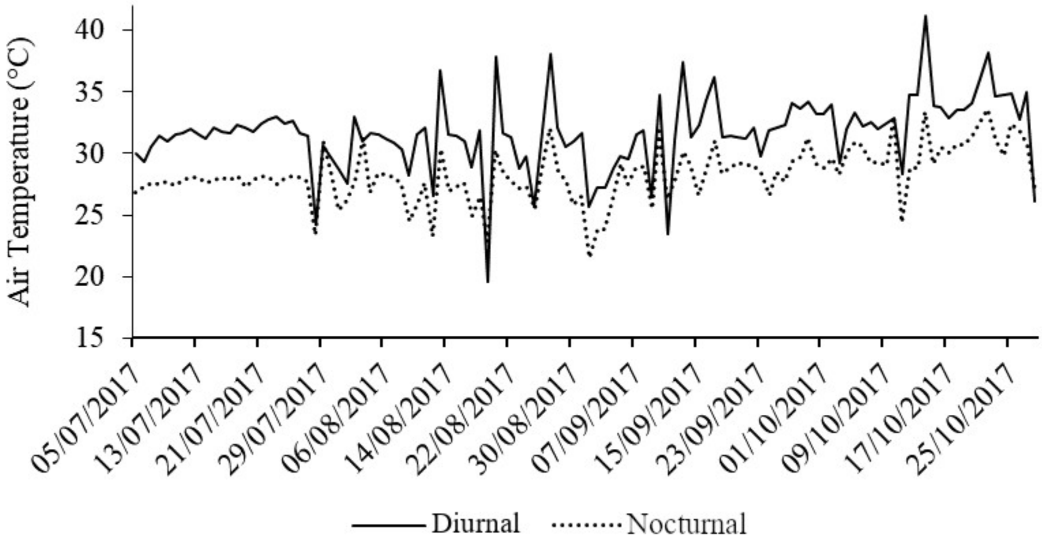

Figure 2. Temporal evolution of daytime and nighttime air temperature in a cotton crop under protected environment, cultivated in the region of Bom Jesus, Piauí.

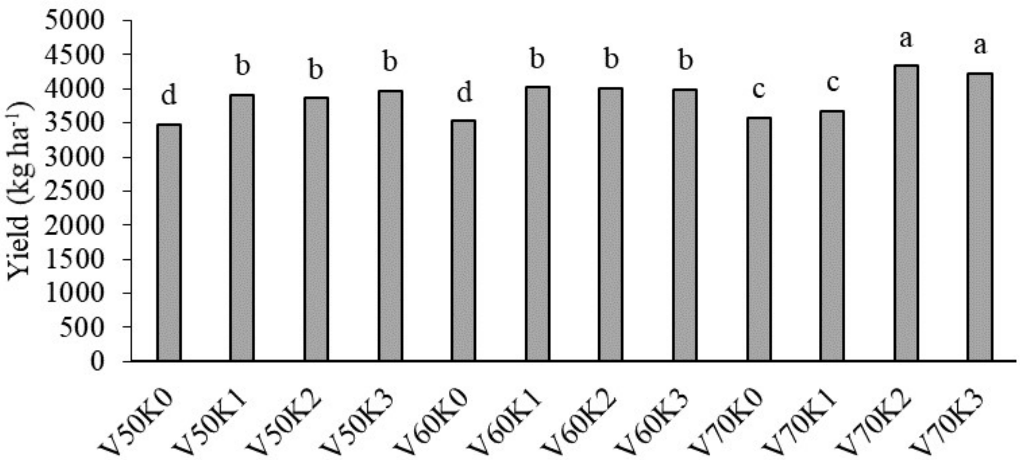

Figure 3. Cotton yield under soil fertility levels, cultivated in a protected environment in the region of Bom Jesus, Piauí.

Treatments composed of interaction: V50, V60 and V70 - for 50%, 60% and 70% of the liming requirement, respectively; and K0, K1. K2, and K3 - for 0; 0.5; 1; and 1.5 of the recommended dose of potassium.
* equal letters between treatments do not differ significantly $p < 0.05$ by Tukey test.

From the analysis of variance (Table 2), it was verified that there was no significant interaction between levels of base saturation (V%) and potassium fertilization for all the evaluated traits, indicating that the factors interfere in the characters independently. Base saturation levels and potassium fertilization rates did not affect plant height at any of the evaluated times, with no adjustment to any mathematical model (Table 2).

Table 2. Summary of the analysis of variance for the variables Plant height (cm) - PH, Stalk diameter (mm) - SD, Number of nodes (number) - NN and Leaf area (cm^2) - LA in cotton plants under soil fertility levels at 20, 40, 60 and 80 days after emergence (DAE), cultivated in a protected environment in the region of Bom Jesus - PI, Brazil.

Var.	S.V.	D. F.	Mean Squares			
			20 DAE	40 DAE	60 DAE	80 DAE
PH (cm)	V%	2	21,5^{ns}	21,97^{ns}	32,14^{ns}	32,74^{ns}
	Linear	1	3,07^{ns}	15,12^{ns}	20,96^{ns}	21,61^{ns}
	Quadratic	1	1,72^{ns}	28,82^{ns}	43,33^{ns}	43,87^{ns}
	Potassium	3	13,48^{ns}	20,83^{ns}	42,56^{ns}	34,63^{ns}
	Linear	1	16,64^{ns}	14,11^{ns}	48,23^{ns}	41,82^{ns}
	Quadratic	1	23,24^{ns}	28,21^{ns}	73,51^{ns}	38,88^{ns}
	V% * Potassium	6	8,01^{ns}	4,57^{ns}	10,82^{ns}	7,90^{ns}
	CV (%)		10,47	5,34	5,86	6,73
SD (mm)	V%	2	0,0002^{ns}	1,41**	1,93^{ns}	1,73^{ns}
	Linear	1	0,62^{ns}	0,22^{ns}	0,26^{ns}	0,12^{ns}
	Quadratic	1	0,56^{ns}	2,59**	3,60^{ns}	3,35^{ns}
	Potassium	3	0,0009^{ns}	0,67**	0,15^{ns}	0,45^{ns}
	Linear	1	0,0007^{ns}	0,15^{ns}	0,20^{ns}	0,65^{ns}
	Quadratic	1	0,0016^{ns}	1,42**	0,22^{ns}	0,15^{ns}
	V% * Potassium	6	0,0005^{ns}	0,12^{ns}	0,81^{ns}	0,35^{ns}
	CV (%)		9,64	3,92	9,99	8,28
NN	V%	2	0,33^{ns}	0,14^{ns}	0,56^{ns}	2,77*
	Linear	1	0,00^{ns}	0,03^{ns}	0,28^{ns}	3,78*
	Quadratic	1	0,66^{ns}	0,26^{ns}	0,84^{ns}	1,76^{ns}
	Potassium	3	1,13^{ns}	0,52^{ns}	1,11^{s}	1,13^{ns}
	Linear	1	0,00^{ns}	0,41^{ns}	0,60^{ns}	0,14^{ns}
	Quadratic	1	3,00^{ns}	0,74^{ns}	0,33^{ns}	3,00^{ns}
	V% * Potassium	6	0,47^{ns}	0,34^{ns}	1,17^{ns}	0,07^{ns}
	CV (%)		14,34	7,58	6,35	7,77
LA (cm^2)	V%	2	2394,63^{ns}	69167,03^{ns}	254948,93^{ns}	180058,26^{ns}
	Linear	1	3662,25^{ns}	105451,60^{ns}	508627,19^{ns}	251272,58^{ns}
	Quadratic	1	1127,01^{ns}	32882,47^{ns}	1270,66^{ns}	108843,95^{ns}
	Potassium	3	18423,37**	86357,22^{ns}	739531,53**	489205,98**
	Linear	1	4131,41^{ns}	208760,01^{ns}	2151686,38**	1059445,58**
	Quadratic	1	13739,01**	34616,64^{ns}	66694,64^{ns}	176125,82^{ns}
	V% * Potassium	6	10367,17^{ns}	68591,37^{ns}	282247,80^{ns}	134514,56^{ns}
	CV (%)		18,76	19,12	20,09	19,77

** significant at 0.01 probability; * significant at 0.05 probability; ns not significant by Tukey's test.

Also in Table 2, significant effects were verified at the level of base saturation (V%) and potassium fertilization, respectively, on plant growth in Stem diameter (SD) at 40 days after emergence, with adjustments to the regression model (Figure 4A), however, there was no significant effect for the other evaluation times. Regarding the number of nodes (NN) per plant, it was observed that the potassium doses did not affect significantly in any of the evaluated times, while for base saturation a significant difference was observed at 80 DAE. In a joint analysis of the results of the variables number of nodes and plant height, it is possible to infer that saturation by soil bases changes the number of nodes without affecting the height, being, therefore, a favorable factor, as it changes the number of productive branches and, consequently of production, without excessive vertical growth, increasing the risk of lodging. It is known that Ca and Mg play a key role in the growth of plant tissues (TAIZ and ZEIGER, 2003), which may have promoted greater branching and, as a consequence, a greater number of nodes. Base saturation had no significant effect on Leaf Area (LA) at all evaluated times. Furthermore, the application of different doses of potassium in the soil had a significant effect on the leaf area of cotton plants at 20, 60 and 80 DAE (Table 7). The quadratic mathematical model was the one that presented the best fit to the data obtained for this variable at 20 DAE (Figure 4B), from which it was verified increases in cotton leaf area with increasing potassium dose up to the maximum limit of 1105.85 mg vase-1 which provided a leaf area of 208.67 cm2. At 60 and 80 DAE, the linear model was the one that best fitted the results obtained. There was a negative linear effect on the leaf area of cotton plants at 60 and 80 DAE, as a function of the increase in the dose of potassium applied to the soil (Figure 4C and 4D).

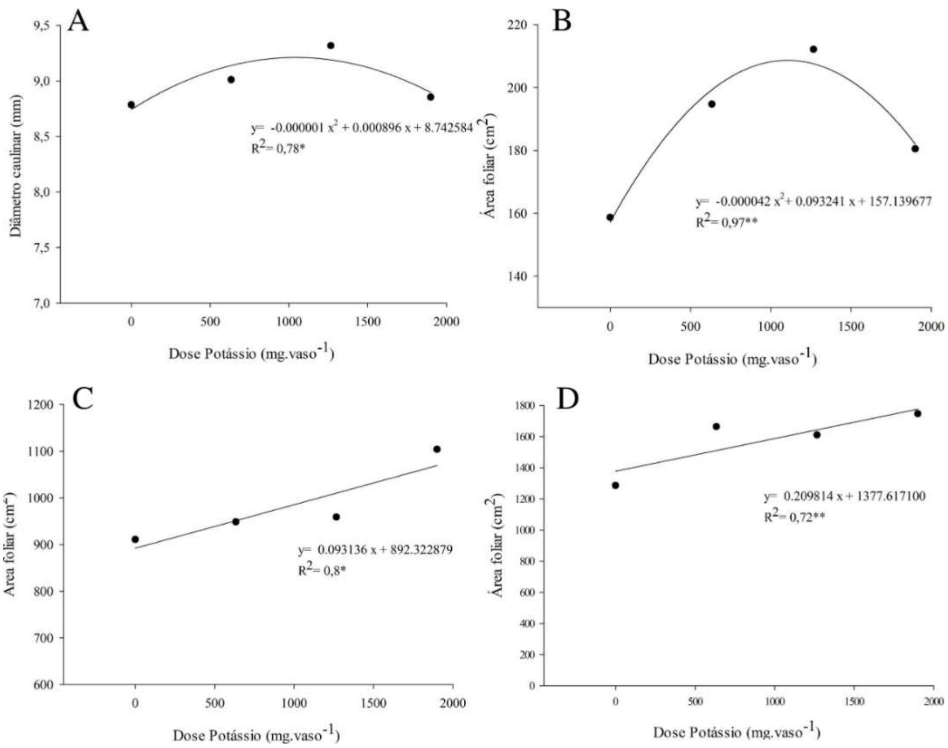

Figure 4. Quadratic regression of stem diameter (mm) at 40 days after emergence (A) and plant height (cm) at 20 days after emergence (B). Linear regression Leaf Area (cm^2) at 60 days (C) and 80 days (D) after emergence in cotton plants under soil fertility levels, cultivated in protected environment in the region of Bom Jesus - PI, Brazil.

K plays an important role in the qualitative characteristics of the cotton plant, positively influencing them from the maintenance and/or increase of the leaf area and regularization of the crop cycle, in addition to providing greater deposition of cellulose on the inner walls of the fibers with a marked improvement in the micronaire index. (CARVALHO and FERREIRA, 2011). According to Cakmak (2005), there is an intrinsic relationship between cell elongation and the concentration of K in the leaves, since the hormones that stimulate the cell elongation process are highly dependent on adequate levels of K in plant tissues.

The cotton plant, regardless of the treatments, presented a cycle of 116 days, configuring a thermal accumulation of 1701.6

°gd. In the different phenological stages, each treatment presented a peculiarity for the manifestation of its phases, this way, different accumulations of thermal units were quantified. Details on the total thermal accumulation (°gd) by phenological stage, as well as its duration in days, can be seen in Table 3.

Table 3. Temperature accumulation (°gd) and duration in days of each stage (ND): Sowing-Emergence (S-E), Emergence-First Flower Bud (E-FB), First Flower Bud-First Flower (FB-FF), First Flower-First Boll (FF-FB) and First Boll-Harvest (CAP-H), in cotton under soil fertility levels, cultivated in a protected environment in the region of Bom Jesus, Piauí.

Tratamentos	S-E	ND	E-FB	ND	FB-FF	ND	FF-FB	ND	FB-H	ND
V50 K0	51,4	4	476,3a	35	403,5a	29	277,3f	18	493,0i	30
V50 K1	51,4	4	466,4b	34	383,9b	28	306,8ce	20	493,0i	30
V50 K2	51,4	4	451,6c	33	368,2c	27	320,7b	21	509,7h	31
V50 K3	51,4	4	451,6c	33	354,8d	26	302,3de	20	541,5f	33
V60 K0	51,4	4	437,8d	32	381,9b	28	304,0de	20	526,4g	32
V60 K1	51,4	4	426,5e	31	379,9b	28	302,3de	20	541,5f	33
V60 K2	51,4	4	426,5e	31	365,5c	27	301,5e	20	556,7e	34
V60 K3	51,4	4	412,5f	30	342,7e	25	310,0cd	21	584,9c	36
V70 K0	51,4	4	426,5e	31	353,0d	26	329,2a	22	541,5f	33
V70 K1	51,4	4	426,5e	31	339,7ef	25	313,0bc	21	571,0d	35
V70 K2	51,4	4	412,5f	30	342,7e	25	279,3f	19	615,6b	38
V70 K3	51,4	4	412,5f	30	334,0f	24	257,5f	18	646,1a	40
Média	51,4	4	435,6	32	362,5	27	300,3	20	551,7	34

Interaction composite treatments: V50, V60, and V70 - for 50%, 60%, and 70% of the liming requirement, respectively; and K0, K1. K2, and K3 - for 0; 0.5; 1; and 1.5 of the recommended dose of potassium.

*Means followed by the same letter in the column do not differ at 5% probability using the Tukey test.

The treatments V70K2 and V70K3 were the most precocious in relation to the beginning of fruiting (appearance of the first boll), not differentiating each other, with the exception of the first floral bud-first flower (FB-FF), when compared to the other treatments, which guaranteed the beginning of the phase at 1085.9 °gd (78 days) and 1055.4 °gd (76 days) accumulated, respectively, on the other hand, they needed more time for the boll maturation phase (FB-H). On the other hand, the V50K0 treatment showed the opposite behavior, with a higher average in the initial stages and lower in the final stages.

Higher potassium doses are associated with the shortening of the Emergence-First Flower Bud (E-FB), First Flower Bud-First Flower (FB-FF) phases, since the thermal accumulation is always statistically lower than treatments associated with K2 doses. and K3 (Table 3). In the FF-FB and FB-H phases this relationship is inverted. The thermal accumulation for the FM 975 WS variety was higher, both by phenological stage and total, than the average data for the cotton crop described by Chiavegato et al. (2009), which show the variation of thermal units accumulated from sowing to harvest from 1165 to 1250 °gd. It is noteworthy that the data presented here are superior even considering the minimum basal temperature that the authors used (15.5 °C).

It must be noted that there are no current works that directly relate the thermal accumulation with the phenology of cotton, especially for the variety addressed, so there is a scientific lack on this subject. Thus, the importance of the present work is emphasized, since the results presented allow a better management in the cultivation of the culture.

Considering that air temperature is the meteorological element with the greatest impact on cotton development, which significantly affects its phenology, leaf expansion, internode elongation, biomass, among others (CHIAVEGATO et al., 2009), it is useful to have models that allow estimating biometric variables of the plant as a result of its sensitivity to temperature. Thus, quadratic polynomial regression models are shown in Table 4, according to the adjustments obtained in Figure 5.

Table 4. Quadratic regression models and correlation coefficients obtained through the relationship between Plant Height (cm) - PH, Stalk Diameter (mm) - SD, Number of Nodes (number) - NN, Number of Leaves (number) - NL, Veins Length (mm) - VL, Leaf Area (cm2) - LA and Average Air Temperature in cotton plants under soil fertility levels, cultivated in a protected environment in the region of Bom Jesus - PI, Brazil.

Var.	Tratamentos					
	V50K0	R	V50K1	R	V50K2	R
PH	-12,081T^2+737,62T-1118	0,91	-11,776T^2+718,6T-108	0,93	-12,22T^2+746,63T-11318	0,92
SD	-3,0778T^2+187,06T-2829,7	0,91	-2,9682T^2+180,52T-2732	0,90	-2,5831T^2+157,39T-2385,6	0,84
NN	-2,3637T^2+143,81T-2173,1	0,92	-1,8525T^2+112,95T-1707,9	0,85	-1,8462T^2+112,96T-1713,6	0,93
NL	-4,0286T^2+255,37T-3999,9	0,99	-6,1397T^2+381,39T-5876,6	0,99	-6,4495T^2+401,74T-6205,6	0,99
VL	-0,5446T^2+32,36T-469,4	0,28	-0,3417T^2+19,92T-278,77	0,35	-0,5056T^2+29,882T-429,72	0,43
LA	-206,47T^2+12745T-19527	0,96	-255,42T^2+15637T-237861	0,92	-323,15T^2+19796T-301433	0,99
	V50K3	R	V60K0	R	V60K1	R
PH	-12,021T^2+735,18T-11157	0,93	-11,674T^2+713,19T-10809	0,92	-12,389T^2+757,31T-11486	0,94
SD	-2,37T^2+144,78T-2199,5	0,85	-2,4772T^2+151,41T-2301,2	0,85	-2,6063T^2+158,94T-2410,8	0,83
NN	-1,9807T2+120,89T-1831	0,88	-1,5507T^2+95,344T-1451,7	0,84	-2,0534T^2+125,31T-1897,6	0,87
NL	-6,5021T^2+405,31T-6264	0,99	-9,4871T^2+580,54T-8834,1	0,99	-4,668T^2+295,09T-4612,9	0,99
VL	-1,1709T^2+70,006T-1033,6	0,58	-0,5031T^2+29,435T-419,15	0,44	-0,1093T^2+6,5353T-86,426	0,03
LA	-513,27T^2+31235T-473059	0,99	-378,76T^2+22908T-344929	0,90	-139,98T^2+8936T-140717	0,99
	V60K2	R	V60K3	R	V70K0	R
PH	-11,838T^2+723,24T-1096	0,93	-11,838T^2+723,24T-1096	0,93	-12,078T^2+737,6T-11179	0,93
SD	-2,8089T^2+171,33T-2599,4	0,84	-2,4195T^2+148,07T-2252,9	0,85	-2,2287T^2+136,46T-2076,9	0,84
NN	1,9381T^2+118,24T-1789,4	0,90	-2,066T^2+126,2T-1913,2	0,83	-4,0178T^2+255,4T-4009,8	0,91
NL	-5,6258T^2+352,39T-5467,2	0,99	-6,6285T^2+412,33T-6361,3	0,99	-4,0178T^2+255,4T-4009,8	0,99
VL	-0,5846T^2+34,447T-495,22	0,91	-1,067T^2+63,555T-933,68	0,71	-0,9519T^2+56,862T-837,23	0,71
LA	-430,98T^2+26248T-397745	0,99	-526,9T^2+32002T-483844	0,99	-307,9T^2+18863T-287328	0,99
	V70K1	R	V70K2	R	V70K3	R
PH	-11,173T^2+683,77T-10376	0,92	-12,532T^2+765,87T-11613	0,92	-11,107T^2+678,59T-10282	0,92
SD	-2,2551T^2+138,04T-2100,5	0,82	-2,6452T^2+161,21T-2443,9	0,84	-2,6507T^2+161,63T-2451,8	0,87
NN	-2,0085T^2+122,66T-1858,3	0,89	-2,0363T^2+124,43T-1886,1	0,90	-1,5252T^2+93,57T-1421,7	0,83
NL	-4,8985T^2+309,21T-4827,4	0,99	-6,2438T^2+389,41T-6020,7	0,99	-5,3497T^2+335,64T-5214,1	0,99
VL	-0,492T^2+29,259T-423,07	0,93	-0,2004T^2+11,902T-165,08	0,36	-206,47T^2+12745T-195271	0,96
LA	-476,33T^2+29052T-440896	0,99	-382,64T^2+23430T-356745	0,99	-226,07T^2+14103T-218039	0,99

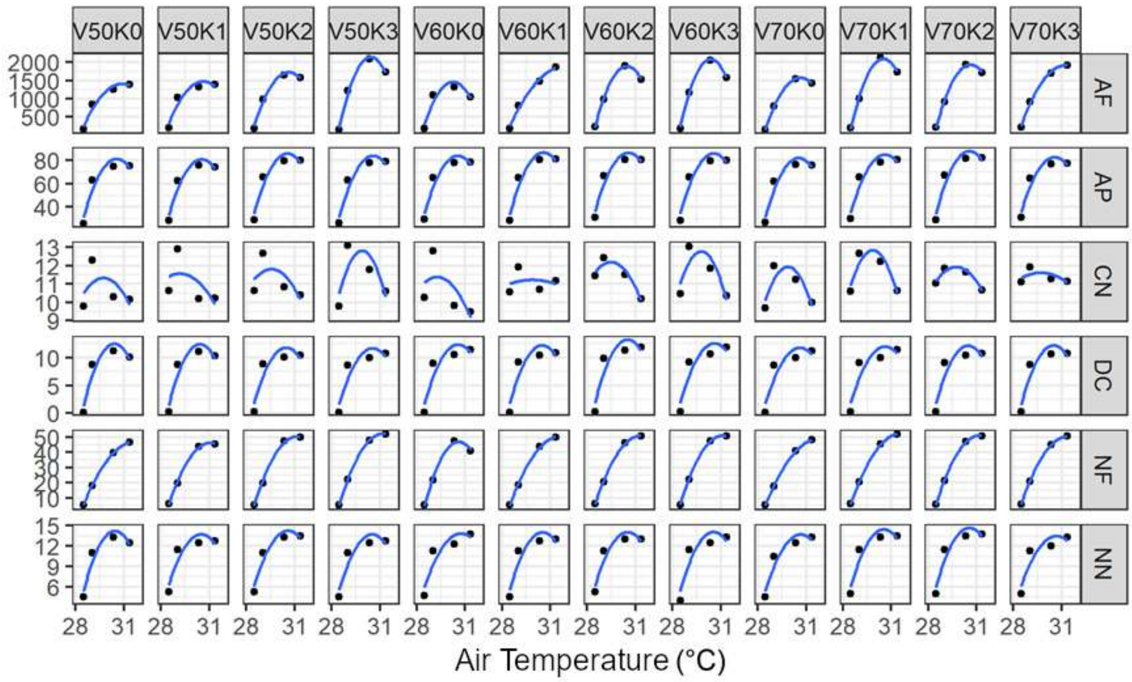

Figure 5: Quadratic regression between air temperature (°C) and plant height (cm) - AP, stem diameter (mm) - CD, number of nodes (number) - NN, number of leaves (number) - NF, leaf length (mm) - CN, leaf area (cm2) - LA in cotton plants under soil fertility levels, cultivated in a protected environment in the region of Bom Jesus - PI, Brazil.

Treatments composed of interaction: V50, V60 and V70 - for 50%, 60% and 70% of the liming requirement, respectively; and K0, K1. K2, and K3 - for 0; 0.5; 1; and 1.5 of the recommended dose of potassium.

As can be seen in Figure 5, the pattern for most variables is similar, in which there is an increase in the phytotechnical variable as there is an increase in temperature, occurring until a point of maximum use and, later, there is a decrease due to a negative effect of the meteorological element, with the exception of the Vein Length (VL).

This has greater expression in temperatures between 29 and 30 °C, being harmed by those around 28 and 31 °C. The variables Plant Height (AP), Stem Diameter (DC), Number of Nodes (NN), Number of Leaves (NF) and Leaf Area (AF) have relationships classified according to the correlation coefficient (R) as strong and very strong, adjusting models that can be used with precision to estimate the growth and development of the cotton plant due to the high values of R, and these equations were significant at the level of 95% of probability by the F test. The Vein Length (VL) showed strong and very strong relationships for treatments V60K2, V60K3, V70K0, V70K1 and V70K3, the others are classified as medium and weak. It is noteworthy that the adjustments for this variable were not significant ($p > 0.05$). It is believed that the behavior of the variation of R in VL as a result of the treatments may be related to the data dispersion itself (Figure 4), there is a pattern in the treatments that obtained medium and weak classification (V50K0, V50K1, V50K2, V50K3, V60K0, V60K1 and V70K2) similar to the others and, as there was no variation in the pattern of the other phytotechnical variables in favor of fertility levels, it is assumed that this factor does not have much influence on the temperature-growth relationship.

In relation to the thermal units, results were obtained similar to those presented for air temperature, in view of their proportionality.

Thus, the models shown in Table 5 result from the adjustments shown in Figure 5.

Table 5. Quadratic regression models and correlation coefficients obtained through the relationship between Plant Height (cm) - PH, Stalk Diameter (mm) - SD, Number of Nodes (number) - NN, Number of Leaves (number) - NL, Vein Length (mm) - VL, Leaf Area (cm2) - LA and Thermal Accumulation (°gd) in cotton plants under soil fertility levels, cultivated in a protected environment in the region of Bom Jesus - PI, Brazil.

Var.	Tratamentos			
	V50 K0	R	V50 K1	R
PH	$-0{,}0001x^2 + 0{,}2353x - 39{,}582$	0,99	$-0{,}0001x^2 + 0{,}2239x - 34{,}103$	0,99
SD	$-3E\text{-}05x^2 + 0{,}0571x - 15{,}508$	0,99	$-3E\text{-}05x^2 + 0{,}0559x - 15{,}12$	0,99
NN	$-2E\text{-}05x^2 + 0{,}044x - 7{,}6388$	0,99	$-2E\text{-}05x^2 + 0{,}0369x - 4{,}8011$	0,97
NL	$-2E\text{-}05x^2 + 0{,}0855x - 22{,}006$	0,97	$4E\text{-}05x^2 + 0{,}114x - 29{,}326$	0,95
VL	$-8E\text{-}06x^2 + 0{,}0114x + 7{,}1521$	0,44	$-6E\text{-}06x^2 + 0{,}0082x + 8{,}9999$	0,38
LA	$-0{,}0018x^2 + 4{,}2224x – 1061$	0,99	$-0{,}0024x^2 + 5{,}0747x - 1215{,}2$	0,99
	V50 K2	R	V50 K3	R
PH	$-0{,}0001x^2 + 0{,}2363x - 36{,}993$	0,99	$-0{,}0001x^2 + 0{,}2332x - 38{,}813$	0,99
SD	$-3E\text{-}05x^2 + 0{,}0513x - 13{,}739$	0,97	$-2E\text{-}05x^2 + 0{,}0482x - 12{,}982$	0,97
NN	$-2E\text{-}05x^2 + 0{,}0361x - 4{,}8502$	0,99	$-2E\text{-}05x^2 + 0{,}0392x - 6{,}2632$	0,99
NL	$-4E\text{-}05x^2 + 0{,}1202x - 32{,}224$	0,94	$-4E\text{-}05x^2 + 0{,}1266x - 33{,}848$	0,97
VL	$-7E\text{-}06x^2 + 0{,}0099x + 8{,}3915$	0,54	$-1E\text{-}05x^2 + 0{,}021x + 4{,}4869$	0,79
LA	$-0{,}0028x^2 + 5{,}9337x - 1527{,}3$	0,99	$-0{,}0045x^2 + 8{,}8793x - 2375{,}4$	0,98
	V60 K0	R	V60 K1	R
PH	$-0{,}0001x^2 + 0{,}2272x - 33{,}827$	0,99	$-0{,}0001x^2 + 0{,}2386x - 38{,}361$	0,99
SD	$-2E\text{-}05x^2 + 0{,}0505x - 13{,}633$	0,97	$-3E\text{-}05x^2 + 0{,}0524x - 14{,}054$	0,97
NN	$-2E\text{-}05x^2 + 0{,}034x - 4{,}5802$	0,96	$-2E\text{-}05x^2 + 0{,}0406x - 6{,}6479$	0,98
NL	$-7E\text{-}05x^2 + 0{,}1593x - 41{,}895$	0,92	$-3E\text{-}05x^2 + 0{,}095x - 25{,}289$	0,96
VL	$-8E\text{-}06x^2 + 0{,}0107x + 8{,}0088$	0,48	$-2E\text{-}06x^2 + 0{,}0039x + 9{,}742$	0,17
LA	$-0{,}0037x^2 + 6{,}7134x - 1649{,}4$	0,99	$-0{,}0009x^2 + 3{,}3992x - 875{,}49$	0,99
	V60 K2	R	V60 K3	R
PH	$-0{,}0001x^2 + 0{,}2287x - 32{,}481$	0,99	$-0{,}0001x^2 + 0{,}2362x - 37{,}216$	0,99
SD	$-3E\text{-}05x^2 + 0{,}0564x - 15{,}133$	0,97	$-2E\text{-}05x^2 + 0{,}0501x - 13{,}537$	0,97
NN	$-2E\text{-}05x^2 + 0{,}0376x - 5{,}1286$	0,99	$-2E\text{-}05x^2 + 0{,}0423x - 7{,}5323$	0,96
NL	$-4E\text{-}05x^2 + 0{,}1104x - 28{,}808$	0,96	$-5E\text{-}05x^2 + 0{,}1268x - 33{,}549$	0,96
VL	$-7E\text{-}06x^2 + 0{,}0088x + 9{,}3199$	0,94	$-1E\text{-}05x^2 + 0{,}0181x + 5{,}9303$	0,86
LA	$-0{,}0036x^2 + 7{,}1764x - 1845{,}7$	0,93	$-0{,}0046x^2 + 8{,}8756x - 2341{,}5$	0,96
	V70 K0	R	V70 K1	R
PH	$-0{,}0001x^2 + 0{,}2313x - 37{,}882$	0,99	$-0{,}0001x^2 + 0{,}2206x - 31{,}54$	0,99
SD	$-2E\text{-}05x^2 + 0{,}0467x - 12{,}57$	0,96	$-2E\text{-}05x^2 + 0{,}0477x - 12{,}776$	0,95
NN	$-2E\text{-}05x^2 + 0{,}0354x - 5{,}3789$	0,99	$-2E\text{-}05x^2 + 0{,}0396x - 5{,}9269$	0,99
NL	$-2E\text{-}05x^2 + 0{,}0859x - 22{,}633$	0,97	$-3E\text{-}05x^2 + 0{,}1011x - 26{,}327$	0,97
VL	$-1E\text{-}05x^2 + 0{,}0163x + 5{,}5434$	0,87	$-1E\text{-}05x^2 + 0{,}0167x + 6{,}3086$	0,96
LA	$-0{,}0025x^2 + 5{,}4194x - 1443{,}8$	0,96	$-0{,}0039x^2 + 7{,}9195x - 2120{,}7$	0,92
	V70 K2	R	V70 K3	R

PH	$-0,0001x^2 + 0,2428x - 38,702$	0,99	$-0,0001x^2 + 0,2151x - 29,044$	0,99
SD	$-3E\text{-}05x^2 + 0,0526x - 14,097$	0,97	$-3E\text{-}05x^2 + 0,0521x - 14,064$	0,98
NN	$-2E\text{-}05x^2 + 0,04x - 6,0906$	0,99	$-2E\text{-}05x^2 + 0,033x - 4,0029$	0,96
NL	$-4E\text{-}05x^2 + 0,1201x - 31,645$	0,96	$-3E\text{-}05x^2 + 0,1082x - 28,182$	0,97
VL	$-5E\text{-}06x^2 + 0,0076x + 9,126$	0,99	$-3E\text{-}06x^2 + 0,004x + 10,168$	0,52
LA	$-0,003x^2 + 6,5395x - 1724,2$	0,93	$-0,0017x^2 + 4,6336x - 1192,4$	0,99

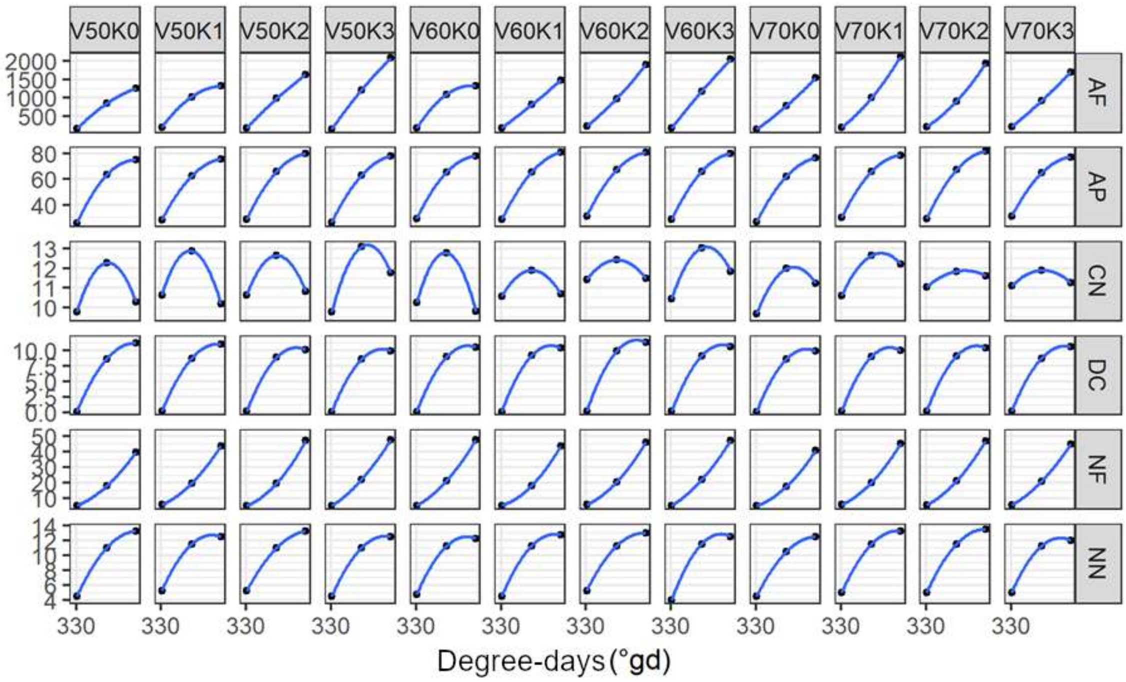

Figure 6. Quadratic regression between heat accumulation (°gd) and leaf area (LA, cm2); plant height (PA, cm); stalk length (SL, mm); stem diameter (SD, mm); leaf number (LE, dimensionless); and node number (NN, dimensionless) in cotton plants under soil fertility levels, cultivated in a protected environment in the region of Bom Jesus, Piauí.

Treatments composed of interaction: V50, V60 and V70 - for 50%, 60% and 70% of the liming requirement, respectively; and K0, K1. K2, and K3 - for 0; 0.5; 1; and 1.5 of the recommended dose of potassium.

When related to thermal accumulation, most phytotechnical variables behave in a more linear way than when compared to temperature, showing only a tendency to stabilization (Figure 5) and not to a decrease as evidenced in Figure 4.

The Vein Length (VL) exhibits the same behavior as mentioned above. Having a relationship characterized as strong and very strong for treatments V50K3, V60K2, V60K3, V70K0, V70K1 and V70K2 and, for the other variables, R ratings were found only as very strong. This way, there is a great fit for most models.

Knowing that both temperatures and the accumulated thermal units are directly related to the availability of energy and plant metabolism, the increase in these factors provided has a positive effect on the parameters evaluated, due to the increase in the photosynthetic rate with consequent greater production of photoassimilates and development plant life (TAIZ; ZEIGER, 2013).

However, there is identification of a temperature limit (32 °C) in which there is a negative effect of this element on plants, for most variables. Osanai et al. (2017) also found impacts of increased air temperature on cotton biometric parameters, such as positive in growth and harmful in yield components.

It is worth mentioning that experiments that aim to evaluate the effects of soil quality factors, such as chemical attributes, in studies on fertilization, for example, are preferably carried out in controllable containers (pots) and in a protected environment, in order to control the effect of biotic and abiotic agents on plants. Additionally, the proposed models are calibrated for use in a protected environment, requiring the execution of more studies of this nature aiming at their validation in the field.

As previously mentioned, despite the record of temperatures outside the optimal range of cotton development, an adequate yield was obtained for the cultivation, and its thermal requirements were met and it was able to manifest its expected potential for the conditions of a protected environment. found in the State of Piauí.

CONCLUSIONS

Soil saturation levels by bases change the stem diameter and the number of nodes of cotton plants. In addition, cotton increases in stem diameter, leaf area and productivity with increasing doses of potassium applied to the soil.

The base saturation of 70% and potassium doses of 126 and 190 kg ha^{-1} contribute to the vegetative growth of the cotton plant, reducing its thermal accumulation until the beginning of fruiting, on the other hand, they need more time for the maturation phase of the bolls. Lower base saturations (50%) and the absence of potassium fertilization or a dose below the recommended one promote a longer vegetative and a shorter reproductive stage.

The region of Bom Jesus, Piauí, despite having unfavorable temperature records for the development of cotton, had meteorological characteristics that allowed the adequate productivity of the crop (3500 and 4500 kg ha^{-1}) supplying its thermal requirements. Base saturation, when associated with higher doses of potassium, is the main factor that contributes to the shortening of the vegetative stage and earlier onset of fruiting.

Air temperature and energy accumulation have significant effects on cotton growth parameters, being directly proportional to most of the variables analyzed.

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