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Mathematical modelling on summer sesame response to moisture and thermal regimes

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ABSTRACT : A field experiment was conducted at instructional farm of soil and water engineering, CAET, JAU, Junagadh during summer season(Feb.-May). The crop was exposed to different moisture regimes by varying the irrigation interval (3, 4 and 5 days irrigation interval) and mulch level (wheat straw mulch @ 5 t/ha and no mulch). It was observed that, sesame yield was significantly influenced by the thermal regimes and moisture regimes by varying water application under drip irrigation. The sesame yield response to seasonal thermal heat units as well as to stage wise thermal heat unit's availabilities could be described well by the quadratic model. The linear form of the model for the yield response to irrigation interval shows that the yield decreases with increase in irrigation interval. The developed model showed that for the 3 days and 4 days irrigation interval, the sesame grain yield increased more rapidly under mulch as compared to no mulch for the lower values of thermal heat units but for the higher values of thermal heat units, the yield decreased more rapidly under mulch as compared to no mulch. The sesame yield response to seasonal irrigation depth could be found linear indicating that the applied water was less than the crop evapotranspirations (ET_c) or the optimal water requirements and yet there is a scope for increasing the yield by increased water application.

KEY WORDS : Mathematical modelling, Thermal regimes, Moisture regimes

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Water resources of a country constitute one of its vital assets. India occupies only 329 M-ha geographical area, which forms 2.4 per cent of the world's land area; it supports over 15 per cent of the world's population. The population of India as on 31 March 2011 stood at 1,210, 193, 422 persons. Thus, India supports more than 1/6th of world population, 1/50th of world's land and 1/25th of world's water resources. Drip irrigation is one of the best and latest methods for efficient utilization of irrigation water. It is an efficient method of application of water in which, the water is applied at low rate over long period of time at frequent intervals with low-pressure delivery system, in order to avoid water stress to the plant. Drip irrigation provides high water use efficiency, higher crop yield, less labour requirement and relatively low operating cost, less weed growth, less insect and pest attacks, shorter growing season and earlier harvest of the crop. The soil moisture in the upper root zone is evacuated mainly due to soil evaporation and the water stored in the lower portion can be utilized efficiently by plant. To conserve water for a longer period and to reduce evaporation mulching is used. Mulching is the application of any plant residues or other materials to cover the top soil surface.

Thermal regime :

Temperature is an important weather parameter that affects plant growth, development and yield. Photosynthesis produces the sources of assimilates which plants use for growth and development. Temperature and radiation influence the rate of photosynthesis. However, plants also have an obligatory development in time, which must be met if the photosynthetic assimilates are to be converted into economically useful yields of satisfactory quantity and quality. Temperature (and day-length in case of photosensitive crops) influences the developmental sequence of crop growth in relation to crop phonology. Evolutionary changes that have occurred in the biochemical and physical characteristics of photosynthesis have resulted in a large variation between crops in both their optimum temperature requirements and the responses of photosynthesis to changes in temperature, radiation and composition of the atmosphere.

Objective :

To optimize the thermal and moisture regime using crop yield models.

■ METHODOLOGY

A field experiment was conducted at instructional farm of soil and water engineering, CAET, JAU, Junagadh during summer season (Feb-May)-2012 to study the summer sesame response to moisture and thermal regimes with three factorial Strip Plot Design. The experiment comprised of 24 treatment combinations were laid out in Strip Plot Design with four replications. The treatment combination of four levels of thermal regime (four dates of sowing 1st February, 16th February, 1st March and 16th March, 2012) and three levels of irrigation interval *viz.,* 3 days, 4 days, 5 days with drip irrigation and 7 days with surface irrigation without mulch as common to all treatment.

Mathematical modelling :

Sesame yield response to thermal regimes :

The sesame crop has its own optimal input requirements of accumulated heat units, soil moisture, day, night or mean air temperatures, soil warmth, duration of darkness, light intensity, etc. It responds differently to these different factors of environment. These responses and requirements, which determine the growth and development of a plant in a given environment, vary not only between families but also from species to species in the same family and from variety to variety in the same species. In the same variety, they may vary from one stage to another.

The sesame response to accumulated heat units were studied by altering the dates of sowing. Changing the date of sowing, the available heat units during the different growth stages of the sesame could be varied.

Various observations of the water consumption, durations of flowering, pod development and maturity, and sesame yield were observed and recorded. Daily maximum and minimum temperature were and utilized for calculating the available heat units. The base temperature (T_b) was taken as 8.0 ^oC (Ramankutty, 2002). The following expression was used to calculate the heat units (Matt *et al.,* 2011).

$$HU = [\, T_{max} + T_{min} \,]/2 - T_b \qquad \text{.....(1)}$$

where, HU is the heat units, degree-days/day; T_{max} is the maximum temperature of the day (^0C) and T_{min} is the minimum temperature of the day (^0C), Tb is the base temperature for the sesame crop (^0C).

The water use efficiency (kg/ha-mm) and heat use efficiency (kg/ha/ degree-days) were computed by dividing the seed sesame yield (kg/ha) by the seasonal water consumption and accumulated seasonal heat units, respectively.

The mathematical models for the sesame yield response to seasonal heat unit availability (Eq. 2a) and sesame yield response heat unit availability during growth periods (Eq. 2b) was developed through regression analysis. The mathematical models for crop yield response to heat units were fitted. Various forms of the mathematical model were tried and the model having the highest goodness of fit (R^2) was proposed.

$$Y = f\,(THU) \qquad \text{...(2a)}$$

$$Y = f\,(thu_i) \qquad \text{...(2b)}$$

where, Y is sesame yield(kg/ha); THU is total seasonal thermal heat unit availability (degree-days); thu_i, is heat unit availability (degree-days) during the i^{th} growth stage and i is an index for the growth period/stage (i = 0, 1, 2, 3 and 4 for establishment, vegetative development, flowering, pod maturity and pod ripening stage, respectively.)

Modelling sesame yield response to moisture regimes:

A production function is necessary to convert the effect of irrigation management practices into monitory terms. Several approaches have been used to estimate the effect of water consumption on crop yields. The yield production function not only gives insights for economical considerations in irrigation projects but also show physiological and agronomic response of crops to different levels of water applications. The sets of data of sesame yield and water consumption observed in treatments plots were used. The seasonal yield production functions for border and drip irrigation have been empirically determined for field conditions.

$$Y = f(W) \quad \ldots(3)$$

where, Y is the sesame yield and W is the seasonal water consumption of the sesame crop. The regression analysis was carried out to test the various mathematical frames and the best model describing the experimental data for drip irrigation was proposed.

RESULTS AND DISCUSSION

The results obtained from the present investigation as well as relevant discussion have been summarized under following heads :

Crop response to moisture regimes :

The optimum moisture regime during different growth stages is one of the important criterions for maximizing the crop yield from the available land and water resources. Altering the irrigation schedules during the different growth stages of crop can vary the moisture regimes. Numerous irrigation studies have been focused on irrigation scheduling to optimize yield and water use efficiency. The irrigation schedules can be either based on (i) fixed irrigation interval, (ii) soil moisture indicators, (iii) climatic indicators, or (iv) plant indicators. In the present study, the sesame crop was exposed to different moisture regimes by varying the irrigation interval.

Crop response to irrigation interval :

Crop yield response to irrigation interval under different thermal window with mulch and no mulch showd the linear relationship could found between grain yield and irrigation interval for all the thermal windows with mulch and no mulch. The yield decreased with increase in irrigation interval. The reason behind the decreased in yield with increase in irrigation interval was due to prevailed higher moisture stress under infrequent irrigations.

Crop response to seasonal depth of irrigation :

Crop yield response to seasonal depth of irrigation under different thermal window with mulch and without mulch. It could be seen that the linear relationship could found between grain yield and seasonal depth of irrigation for all the thermal windows. The yield decreased with decrease in seasonal depth of irrigation. The water applied was lower than the optimal water requirements and yet there is a scope for increasing the yield by increased water application. The similar results were obtained by Ucan (2007) who reported that the amount of irrigation water applied significantly affected the seed yield of sesame. Significant higher grain yield was recorded with higher water quantities treatments. This supports the results of Foroud *et al.* (1993) and Balasubramaniyan and Dharmalingam (1996), they found that increase in yield was directly related to increased number of irrigations. This is because highest water quantities treatments had a better performance of growth and yield components. Rincon *et al.* (1997) found that moisture stress at different growth stages influenced yield attributes and growth parameters. Tantawy *et al.* (2007) found that water stress reduced yield of sesame and optimum amount of irrigation for sesame was about 4367 to 4728 m^3 / ha.

Effects of thermal regime on crop yield :

The data presented in Table 1 shows that the highest and lowest sesame grain yield of 1131.59 kg/ha and 555.20 kg/ha was observed for the thermal windows of 16th February and 1st February, respectively. The crop yield deceased for the thermal windows later than 16th

Table 1 : Effect of thermal window on grain yield(kg/ha)

Treatments / Thermal window	Grain yield (kg/ha)
W_1=1st February	555.20
W_2=16th February	1131.59
W_3= 1st March	1084.72
W_4=16th March	828.09
S.E. ±	33.36
C.D. (P=0.05)	106.75
C.V. (%)	18.16

Feb.The pod yield of 828.10 kg/ha was found under thermal windows of 16th March as the crop matured rapidly due to higher rate of thermal heat unit availability per day. The highest grain yield under thermal windows of 16th Feb. shows that the crop production can be optimum if the daily thermal heat units availability are around 15, 18, 23 and 24 degree-days/day during the establishment, vegetative, flowering-reproductive and ripening stages, respectively.

Crop yield response to thermal heat unit availability during growth stages :

Daily and cumulative thermal heat units available and its effect on grain yield as shown in Fig. 1 and 2, respectively. The crop yield response to thermal heat unit availability during growth stages are presented separately in Fig. 3, 4, 5, 6, 7 and 8 for different irrigation interval with and without mulch.

It could be seen that the quadratic relationship could be found between grain yield and thermal heat unit for all the stages. The yield decreased with increase in thermal heat unit availability up to certain level for establishment and vegetative stages. This indicated that these two stages require the lower thermal heat units. The reason behind the yield increase after reaching the minimum yield level could not be identified. It was found that the increase in thermal heat unit was due to increase in growing days requirement because of lower rate of thermal heat unit availability per day, which had slow down the physiological growth. The vegetative stage was found most sensitive followed by establishment stage, flowering stage, ripening stage and reproductive stage. The growth stages of sesame affected by the thermal heat availability and the result shows the similarity with

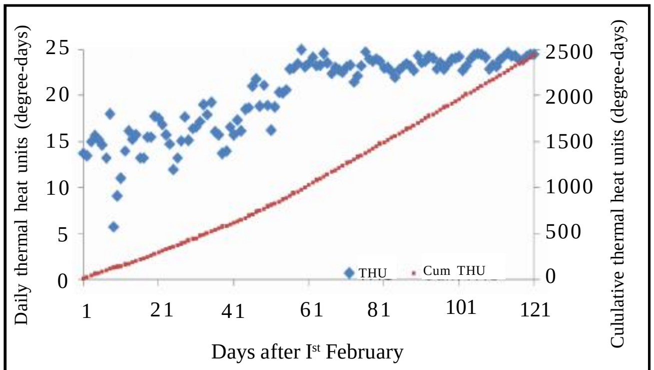

Fig. 1 : Daily and cumulative thermal heat units availability from 1st February

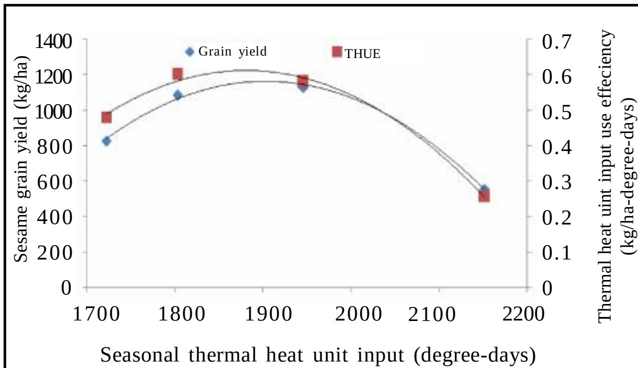

Fig. 2 : Effects of seasonal thermal heat units on sesame grain yield and thermal heat use efficiency

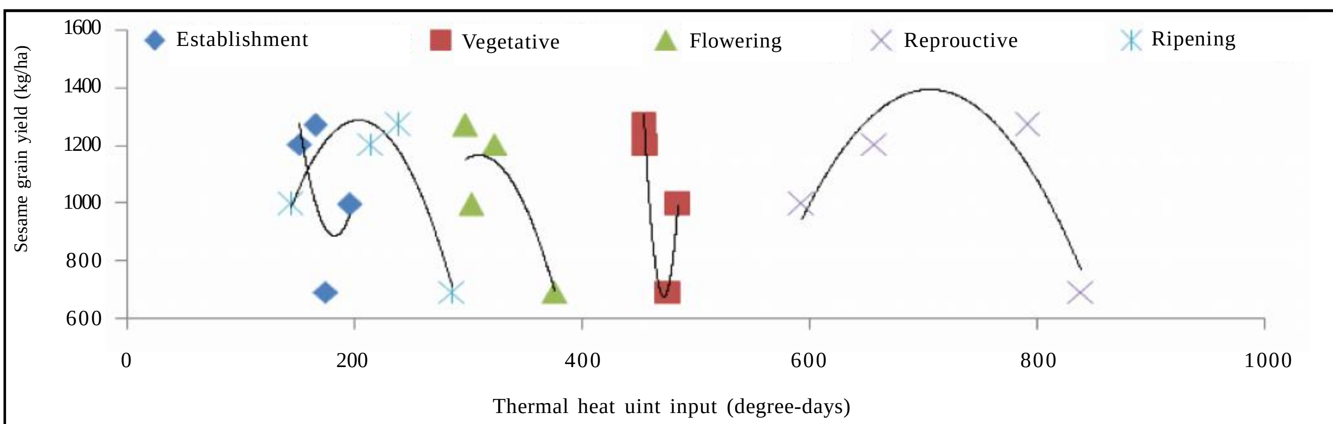

Fig. 3 : Sesame grain yield response to thermal heat units inputs during different growth stages for 3 day irrigation interval under mulch

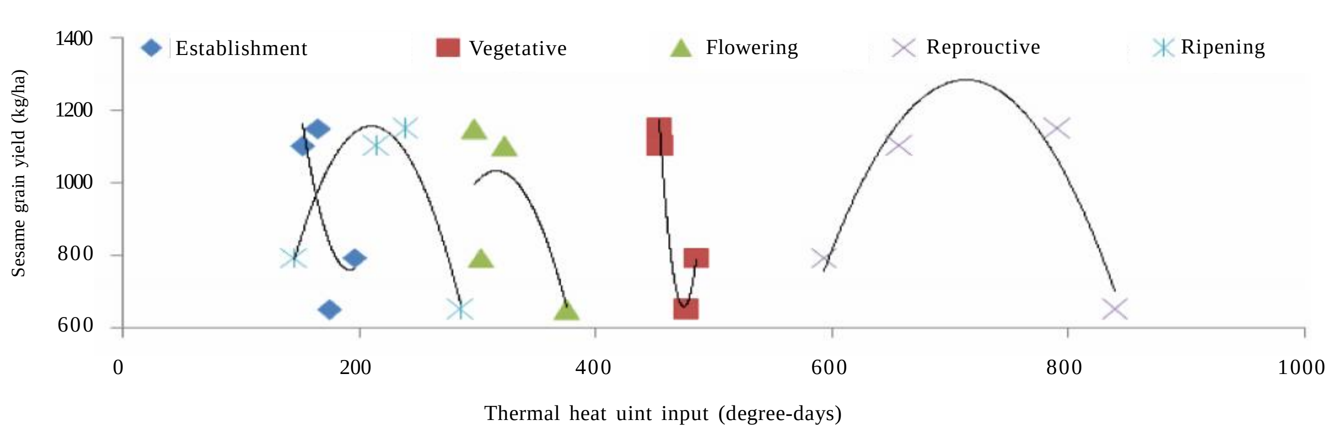

Fig. 4 : **Sesame grain yield response to thermal heat units inputs during different growth stages for 4 day irrigation interval under mulch**

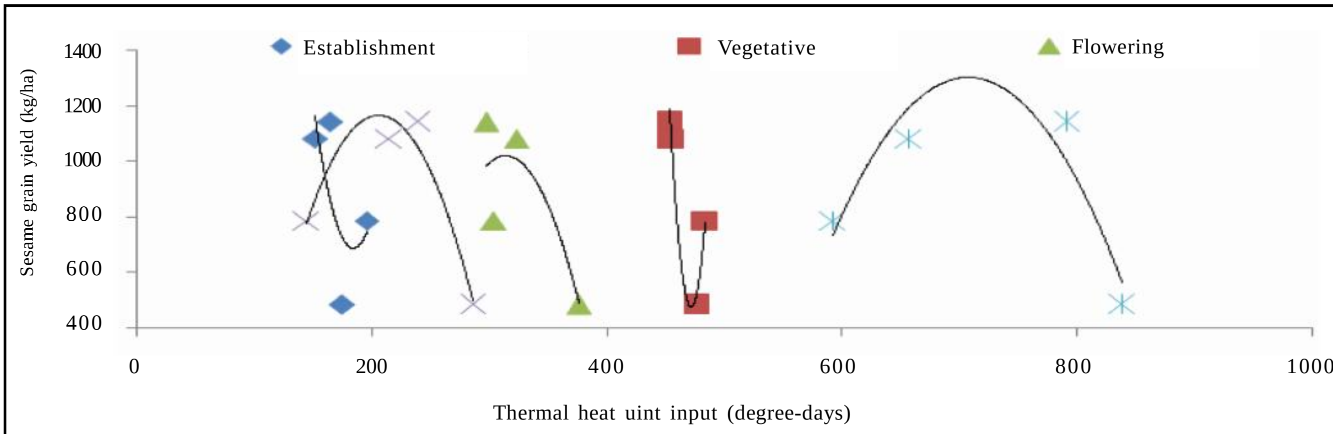

Fig. 5 : **Sesame grain yield response to thermal heat units inputs during different growth stages for 5 day irrigation interval under mulch**

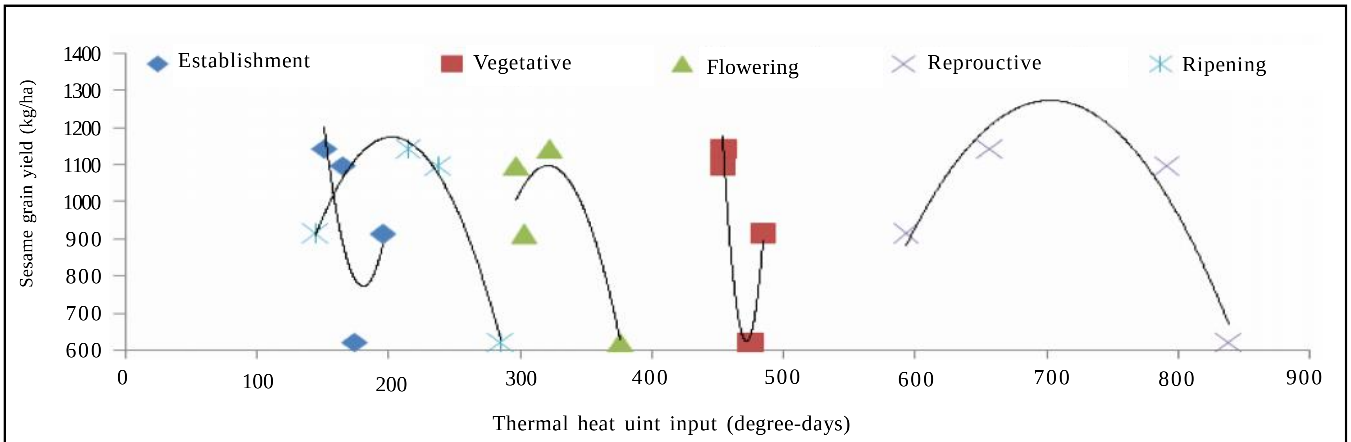

Fig. 6 : **Sesame grain yield response to thermal heat units inputs during different growth stages for 3 day irrigation interval under no mulch**

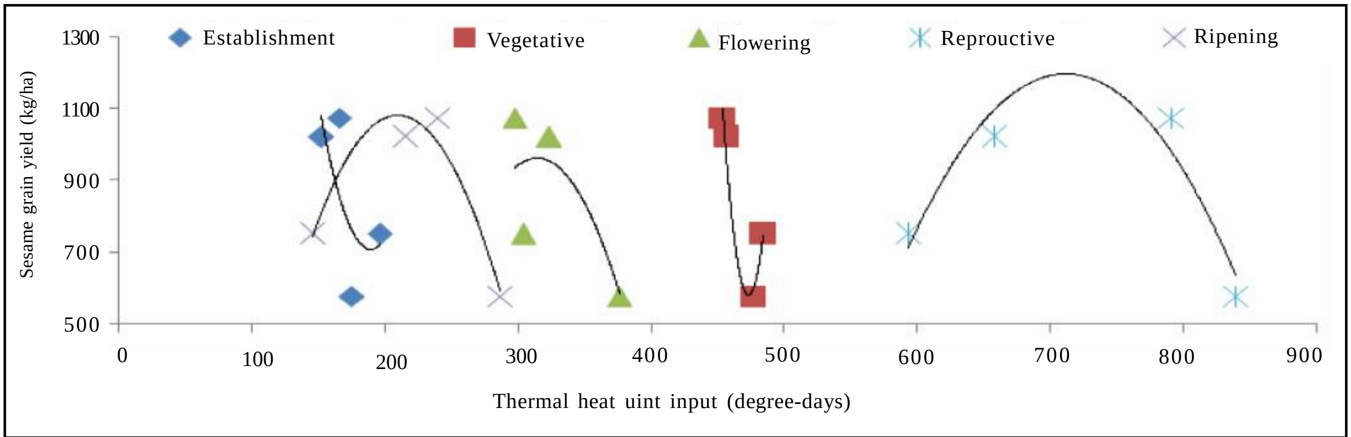

Fig. 7 : Sesame grain yield response to thermal heat units inputs during different growth stages for 4 day irrigation interval under no mulch

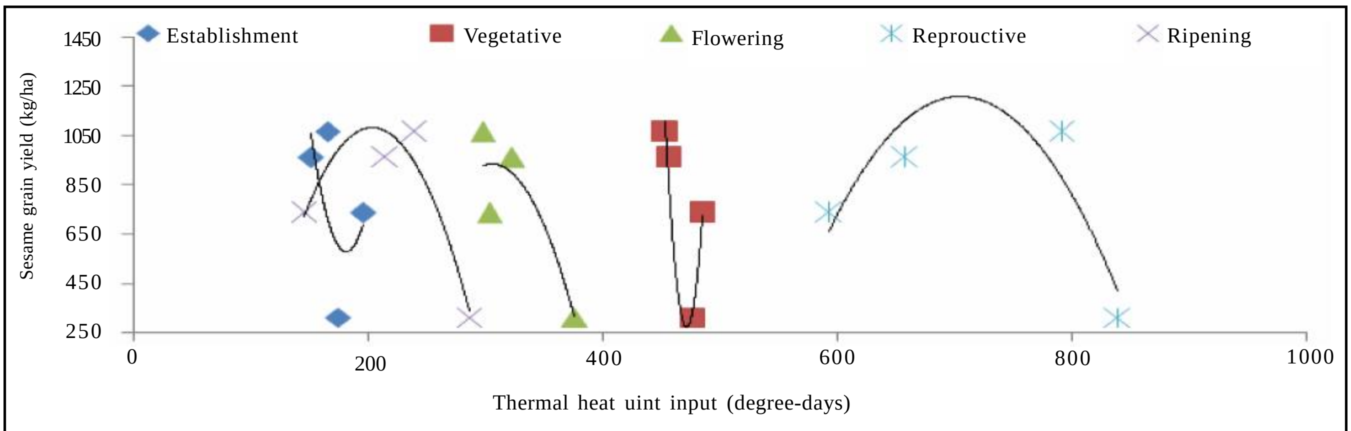

Fig. 8 : Different growth stages for 5 day irrigation interval under no mulch

the result obtained by Tadashi *et al.* (2008) and Michiyama *et al.* (2005) for the flowering stage of sesame stating that low temperature during the flowering period decreased the rate of increase in the flowering-node number, although it prolonged the flowering period. Increased degree days over normal will shorten the vegetative and reproductive stages reported by Langham (2007).

Mathematical modelling :

Yield response to different amounts of inputs either thermal heat units' inputs or irrigation water applied etc. commonly known as yield production model is essential to decide optimum thermal heat unit inputs or irrigation water management. However, with the functional relation between crop yield and inputs remaining some what empirical, it must be determined experimentally for each area of interest. Therefore, the yield production model derived for a particular region should not be used for other region. Nevertheless, they are still useful to predict maximum and minimum crop yields. They can be used for planning and development of land and water resources, projection of national agricultural productions, and predictions of a expected export or import of food crops. The economical feasibility of irrigation water or any inputs is easily achieved with yield production function. The crop yield depends upon duration and level of water and thermal heat unit inputs as well as at which growth stage they are made available. Yield production functions not only gives insights for economic considerations in agriculture project but also show physiological and agronomic response of crop to different levels of water applications and climatic inputs.

Crop yield response to thermal heat unit :

Among the various mathematical frames tried, the second order polynomial (quadratic) relationships were found best fitted as presented in Table 2. The values of the goodness of fit shows that the sesame yield response to seasonal thermal heat units can be described well by the quadratic model. The developed model showed that for the 3 days and 4 days irrigation interval, the sesame

Table 2 : Optimized yield for different irrigation interval

Irrigation interval (days)	Mulch	Model	R^2	Optimized thermal heat units, (degree-days)	Optimized yield (kg/ha)
3rd day	M	$y = -0.0094(THU_s)^2 + 35.58(THU_s) - 32507$	0.999	1892.55	1161.52
	NM	$y = -0.0077(THU_s)^2 + 29.20(THU_s) - 26433$	0.977	1896.10	1250.12
4th day	M	$y = -0.0097(THU_s)^2 + 37.28(THU_s) - 34547$	0.982	1921.65	1272.55
	NM	$y = -0.0093(THU_s)^2 + 35.44(THU_s) - 32796$	0.991	1905.38	967.27
5th day	M	$y = -0.0113(THU_s)^2 + 43.09(THUs) - 39856$	0.996	1906.64	1222.50
	NM	$y = -0.0117(THU_s)^2 + 44.46(THU_s) - 41076$	0.998	1900.00	1161.00

where, THU_s = Seasonal thermal heat unit (degree-days), Y = yield (kg/ha)

Table 3 : Developed models for different growth stages of sesame

Irrigation interval	Mulch level	Growth stages	Models	R^2	Optimize thermal heat unit (Degree-days)	Optimize yield (kg/ha)
3rd day	M	Est	$y = 0.414THU^2 - 151.4THU + 14725$	0.40	182.85	883.24
		Veg	$y = 1.930THU^2 - 1821.THU + 43029$	0.981	471.76	-
		F_l	$y = -0.105THU^2 + 65.27THU - 8930$	0.775	310.81	1213.27
		Rep	$y = -0.035THU^2 + 49.84THU - 16200$	0.815	712.00	1543.04
		Rip	$y = -0.086THU^2 + 35.3THU - 2319.$	0.935	205.23	1303.35
	NM	Est	$y = 0.503THU^2 - 182.3THU + 17285$	0.565	181.21	-
		Veg	$y = 1.675THU^2 - 1581THU + 37354$	0.901	471.94	-
		F_l	$y = -0.159THU^2 + 102.5THU - 15390$	0.829	322.33	7589.26
		Rep	$y = -0.035THU^2 + 49.84THU - 16200$	0.815	712.00	1543.04
		Rip	$y = -0.079THU^2 + 32.20THU - 2093.$	0.993	203.80	962.14
4th day	M	Est	$y = 0.256THU^2 - 98.22THU + 10172$	0.527	191.84	750.94
		Veg	$y = 1.224THU^2 - 1161.THU + 27598$	0.988	474.26	-
		F_l	$y = -0.104THU^2 + 66.35THU - 9461.$	0.548	318.99	1121.51
		Rep	$y = -0.036THU^2 + 52.31THU - 17358$	0.903	726.53	1644.33
		Rip	$y = -0.086THU^2 + 36.46THU - 2682.$	0.960	211.98	1182.34
	NM	Est	$y = 0.276THU^2 - 104.4THU + 10567$	0.484	189.13	694.39
		Veg	$y = 1.337THU^2 - 1266.THU + 30033$	0.988	473.45	-
		F_l	$y = -0.098THU^2 + 61.50THU - 8693.$	0.606	313.78	955.60
		Rep	$y = -0.034THU^2 + 49.50THU - 16408$	0.878	727.94	1608.54
		Rip	$y = -0.082THU^2 + 34.64THU - 2542.$	0.951	211.22	1116.32
5th day	M	Est	$y = 0.455THU^2 - 168.0THU + 16184$	0.450	184.62	676.31
		Veg	$y = 2.038THU^2 - 1925.THU + 45517$	0.978	472.28	-
		F_l	$y = -0.136THU^2 + 85.28THU - 12350$	0.716	313.53	1018.89
		Rep	$y = -0.043THU^2 + 61.09THU - 20322$	0.856	710.35	42019.61
		Rip	$y = -0.104THU^2 + 43.00THU - 3270.$	0.952	206.73	1174.71
	NM	Est	$y = 0.547THU^2 - 198.9THU + 18653$	0.364	181.81	572.01
		Veg	$y = 2.638THU^2 - 2487.THU + 58663$	0.985	471.38	-
		F_l	$y = -0.122THU^2 + 75.05THU - 10522$	0.813	307.58	1020.01
		Rep	$y = -0.043THU^2 + 61.55THU - 20475$	0.783	715.70	1550.60
		Rip	$y = -0.107THU^2 + 43.79THU - 3361.$	0.921	203.22	1058.11

where, Est = Establishment stage, Veg= Vegetative stage, F_l = Flowering stage, Rep = Reproductive stage, Rip = Ripening stage and THU = Thermal heat unit (degree-days) grain yield increased more rapidly under mulch as compared to no mulch for the lower values of thermal heat units but for the higher values of thermal heat units, the yield decreased more rapidly under mulch as compared to no mulch. However, the opposite was found for the models of 5 days irrigation interval. Therefore, for the lower values of the thermal regimes, the mulch helps to maintain the required warmth micro climate for the soil micro-organisms.

Crop yield response to thermal heat unit during different growth stages :

The various mathematical models were tried to fit the observed data of sesame grain yield and heat unit availability during different growth periods like establishment, vegetative, flowering, reproductive and ripening. The best-fitted models are as given in Table 3. It could be seen that the quadratic form of mathematical model was found best fit all the growth stages and for all irrigation interval either under mulch or no mulch.

The heat unit availability during the establishment and vegetative stages had reverse effects on the sesame grain yield. During these two stages, the increased in the heat unit availability decreased yield upto certain level and then after it increased. The reason for the trend during these two stages could not be identified. However, it can be said that higher thermal heat units could be not desirable for the good stand and vegetative development of the sesame crop plants.

Sesame yield response to moisture regimes :

The observed yield and seasonal irrigation water application were used to develop the model. The regression analysis was carried out using the yield data as output and seasonal irrigation water application as input. The developed model for various thermal windows and different irrigation interval under drip with and without mulch were as presented in Table 4 and 5. The linear form of models indicated that yet there can be a scope to increase the yield by increasing the irrigation water applications which indicated that the applied water was less than the crop evapotranspirations (ET_c) and the actual crop evapotranspitation was occurred just equal to irrigation water applied. The developed models were linear in nature which were in contradictory with the results reported by Grimes *et al*. (1969); Grimes and EI-

Table 4: Sesame yield response to seasonal water application

Thermal window	Mulch level	Model	R^2
1-Feb.	Mulch	y = 3.484W - 724.9	0.997
	No Mulch	y = 5.209W - 1489	0.999
16-Feb.	Mulch	y = 1.062W + 807.8	0.985
	No mulch	y = 0.248W + 989.7	0.993
1-Mar.	Mulch	y = 1.317W + 704.2	0.980
	No mulch	y = 1.868W + 439.2	0.999
16-Mar.	Mulch	y = 2.939W + 111.5	0.985
	No mulch	y = 2.433W + 181.2	0.991

where, W = Optimized seasonal depth of irrigation (mm), Y = yield (kg/ha)

Table 5 : Sesame yield response to irrigation interval

Thermal window	Mulch	Model	R^2 -value
1-Feb.	Mulch	y = -105.7I + 818.9	0.890
	No mulch	y = -154.9I + 812.8	0.857
16-Feb.	Mulch	y = -65.49I + 1316.	0.813
	No mulch	y = -16.42I + 1110.	0.941
1-Mar.	Mulch	y = -61.19I + 1250.	0.871
	No mulch	y = -90.17I + 1221.	0.958
16-Mar.	Mulch	y = -104.9I + 1067.	0.780
	No mulch	y = -87.91I + 974.6	0.804

where, I = Irrigation interval (days), Y = yield (kg/ha)

Zik (1990); Wanjura *et al*. (2002) and Rank (2006) for the cotton crop. A substantial body of previous work had been reviewed by Vaux and Pruitt (1983) and ET production function was derived for a variety of agricultural crops. They concluded that the yield of different crops gave as linear function of seasonal consumptive use.

Summary and conclusion :

The sesame yield response to seasonal thermal heat units as well as to stage wise thermal heat unit's availabilities could be described well by the quadratic model. The sesame yield response to seasonal irrigation depth could be found linear indicating that the applied water was less than the crop evapotranspirations (ET_c) and the actual crop evapotranspiration was occurred just equal to irrigation water applied. The linear form of the model for the yield response to irrigation interval shows that the yield decreased with increase in irrigation interval which is a quite common as the infrequent irrigation results in higher moisture stress between two consecutive irrigations.

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