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Phenology, latent heat flux and evaporative fraction in sunflower under different photo-thermal environments

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ABSTRACT

Sunflower was grown in four different sowing dates with 3 irrigation regimes to create different photo-thermal environments. Duration of important phenological stages and productivity were found to be higher in winter sown crop which might be attributed to optimum photo-thermal environment. Crop duration and productivity were reduced when temperature increased during summer and rainy seasons. The day length was found to be influential at vegetative stage but no role was found in reproductive phase of the crop. The latent heat flux varied with the crop growth stage and moisture availability ranged between 8.55 to 19.11 MJ m^{-2} day^{-1} in different years and cropping season. During pick growth stage (47-97 DAS), ET consumed most of the energy, as a result evaporation fraction (EF) was higher during those days which ranged between 80-93% under different sowing dates in the first year and between 70-95% in different growth stages of second year.

Key words: Sunflower, phenology, radiation use efficiency, crop water use, energy balance

Sunflower crop is cultivated in eastern India during different cropping seasons (dry and wet). High temperature during summer while excess rainfall, non availability of optimum photosynthetically active radiation (PAR) during rainy season are the main limiting factors to grow the crop in the region with optimum productivity. As a result, productivity of the crop is far below when compared with the productivity of other major producers of the crop like Russia, Ukraine, Argentina and China (average world's productivity is 1271 kg ha^{-1}). Development rate and duration of phenological stages were largely determined by prevailing temperatures and higher temperatures reduced the vegetative and reproductive phases of the crop; as a result, crop growth parameters and productivity were also decreased (Goyne *et al.*, 1990; Flagelia *et al.*, 2002). Some earlier studies also reported that phenological devel-opment rate of the crop was influenced by both environmental and genetic conditions (Aiken, 2005; Font *et al.*, 2008; Craufurd and Wheeler, 2009). With regard to response of day length on duration of the crop, contrasting information is available. Some earlier studies indicated that short days could accelerate sunflower development (Dyer et al., 1959; Schuster and Boye, 1971, Doyle, 1975). While data from studies at several locations demonstrated that photoperiod could be ignored when modeling sunflower development (Robinson et al., 1967; Goyne et al., 1989).

The energy budget of the active surface such as vegetation can be described by the energy balance equation in a steady state form by,

$$R_n = \lambda E + H + G + ph$$

Where R_n is the net radiation, λE is the latent heat flux, ë is the latent heat of vaporaization of water, H is the sensible heat flux, G is the sum of the soil heat flux, *ph is* energy used for photosynthesis. Under most conditions, the net storage of heat by soil-water and the energy captured by photosynthesis are small, and thus the equation can be reduced to:

$$R_n = \lambda E + H + G$$

Understanding the energy balance under different photo-thermal environments will provide information on crop water requirement and effective irrigation scheduling under limited supply of water (Shen et al., 2004; Figuerola and Berliner, 2006). Bowen ratio micro-metrological method was used by many authors (Shen et al., 2004, Kar and Kumar, 2009) to quantify latent heat flux and evaporative fraction.

Keeping the importance of above points in view, in this investigation an attempt was made to correlate phenological development rate of the crop with maximum temperature, minimum temperature and day length to identify suitable sowing period when photo-thermal environments, were suitable for higher crop productivity. Latent heat flux and water use efficiency of the crop were also computed under different photo-thermal environments

MATERIALS AND METHODS

The on-farm experiment was carried out during 2007-08 and 2008-09 at Bahasuni watershed of Dhenkanal district, Orissa, India (Latitude 20°60′ North and Longitude of 85°57′ East). As per the India Meteorological Department, the study area has 4 climatic seasons viz., rainy or southwest monsoon (June to September), retreating monsoon (October-November), winter (December-February) and pre monsoon or summer (March-May) seasons. About 72% of total annual rainfall (1440 mm) occurs during southwest monsoon period, in post monsoon or other seasons, rainfall is meager and erratic and cropping may not be possible without supplemental irrigations in those seasons. The soil texture of the study area varied from sandy loam to sandy clay loam.

Sunflower cv 'KBSH-1' was grown four times in a year dates (S_1= 23rd June, S_2= 18th October, S_3= 23rd November, S_4= 3rd January in 2007 and S_1= 25th June, S_2= 17th October, S_3= 26th November, S_4= 3rd January in 2008) following standard package of practice with five irrigations (four leaved stage + flower bud stage + beginning of flowering stage + seed formation stage + seed filling stage).

Phenological developmental rate from emergence to flowering, flowering to seed filling, seed filling to maturity was correlated with prevailing maximum temperature, minimum temperature and day length as per the procedure proposed by Hammer *et al.,* (1982) and Rezadoust *et al.,* (2010).

1/D = f (t) x f (p)

f (t) and f (p) are functions of day length and temperature, respectively and D is the number of days between two particular phenological stages.

Phenological sates were identified as per the following characteristics:

Emergence: The day when 50% germination took place in plot by unfolding the cotyledons completely.

Fourth leave stage: The vegetative stage when four leaves unfolded and their leaf stalks also became visible.

Flower bud: The day when 50% of plants in plot produced terminal bud which looked like a miniature flower head rather than a cluster of leaves. The flower bud was visible in the middle of apical rosette of leaves.

Beginning of flowering stage: The day when in 50% plants the inflorescence started to open. When viewed from directly above, immature ray flowers were visible. The ray florets started unfolded and still perpendicular to the plane of the disk (capitulum).

Seed formation stage: Pollination completed and seed production started in 3 outermost rings of florets.

Seed filling stage: Seed filling started and when 20% of seeds have reached final size. The ray florets started to shed but back of the disk was still steel green. The seeds in the outermost circle had become darker and their skins started hardening.

Maturity: The time when 90% of disk in a plot became brown, the seed hardened, turned into black colour and moisture percentage dropped to 10-15%.

Latent heat flux and surface energy balance were computed using Bowen ratio (β) energy balance method which was used by many authors (Shen et al. 2004, Kar and Kumar, 2009).

$$\lambda E = \frac{(R_n - G)}{(1 + \beta)}$$

On the other hand,

$$\text{Bowen ratio } (b) = \frac{\text{Sensible heat loss (H)}}{\text{Evaporative heat loss } (\lambda E)}$$

$$= \frac{c_p P_a}{L\varepsilon} \frac{(T_2 - T_1)}{(e_2 - e_1)}$$

Where, C_p: Specific heat capacity of air (1 J g^{-1} ^{o}C^{-1})

P_a: Atmospheric pressure (101.3 kPa)

L: Latent heat of vaporization (2449 J g^{-1})

ε: Ratio of the molecular weight of water to that of air (0.622)

$$\text{So, } \beta = \frac{(1 \times 101.3)(T_2 - T_1)/z_2 - z_1}{(2449 \times 0.662)(e_2 - e_1)/z_2 - z_1} = 0.667 \frac{(\delta T / \delta z)}{(\delta e / \delta z)}$$

R_n-G =available energy, T_1 is the temperature at height, z_1, T_2 is the temperature at height, z_2, e_1 is the vapour pressure at height, z_1, e_2 is the vapour pressure at height, z_2.

R_n was measured using BABUC M net radiometer. The soil heat flux 'G' was computed with the equation, Gs=0.4*R_n (Exp(-K*LAI)), where 'K' is the extinction coefficient, LAI=Leaf area index (Kar and Kumar, 2009).

The sensors to measure temperature, humidity and wind velocity were installed inside the cropped field on a tower at a distance of 0.5 m which measures theses parameters

Table 1: Photo-thermal environments during crop growth period as influenced by different sowing dates

Sowing dates	Maximum temperature (^{O}C)			Minimum temperature (^{O}C)			Day length (hrs)			Solar radiation (MJ m^{-2})			Rainfall (mm)		
	V_F	F_SF	SF_M	V_F	F_SF	SF_M	V_F	F_SF	SF_M	V_F	F_SF	SF_M	V_F	F_SF	SF_M
S1: 2007-08	32.2	32.8	31.7	24.7	24.8	24.1	13.8	13.3	12.7	16.7	15.3	17.3	328	255	345
2008-09	31.8	31.6	31.1	25.1	25.2	24.5	13.7	13.4	13.6	15.7	14.8	17.1	399	302	198
S2: 2007-08	28.1	27.3	27.8	16.4	15.5	16.3	11.3	10.3	11.2	20.8	21.8	21.9	10.1	2.5	3.9
2008-09	27.5	25.9	28.6	15.1	15.2	16.4	11.5	10.4	11.3	19.4	21.2	21.5	5.5	0.0	0.0
S3: 2007-08	27.9	29.1	29.8	16.1	16.1	17.1	11.6	11.5	11.4	20.2	20.3	22.5	12.2	5.0	4.8
2008-09	27.7	29.4	29.3	16.4	17.4	18.0	11.9	11.2	11.5	20.4	21.5	22.0	5.4	0.0	0.0
S4: 2007-08	29.5	34.4	35.8	18.5	18.5	22.3	12.8	12.3	12.5	22.2	23.3	27.8	5.0	3.8	4.5
2008-09	30.9	34.6	36.3	18.1	18.6	22.1	12.6	12.9	12.6	23.1	22.8	26.9	0.0	0.0	7.1

V_F: Vegetative to flowering, F_SF: Flowering to seed filling, SF_M: Seed filling to maturity

Table 2: Days to flowering, seed filling and maturity as influenced by sowing dates and irrigation regimes

Factors	Days to 50% flowering	Days to 50% seed filling	Days to Maturity
I. Sowing Dates			
S_1	^{D}52.1	^{D}66.9	^{C}96.5
S_2	^{B}61.4	^{B}79.1	^{A}111.6
S_3	^{A}63.8	^{A}80.5	^{A}111.2
S_4	^{C}56.2	^{C}71.6	^{D}98.6
Significance	S	S	S
II. Irrigation Levels			
I_1	^{A}58.8	^{A}73.6	^{B}101.2
I_2	^{A}58.3	^{A}73.1	^{A}104.0
I_3	^{A}59.7	^{A}74.3	^{A}105.7
Significance	S	S	S
Interactions:			
Sowing date × Irrigation	NS	NS	NS

S= Significant at 0.05% probability level, NS = Non significant

at 1-hour interval at 3 different heights. The output of all meteorological sensors were recorded with a datalogger and retrieved afterwards with the help of a PC.

A dimensionless parameter, evaporative fraction (EF) was used to characterize surface energy partitioning, EF is defined as

$$EF = \left(\frac{LE}{R_n - G}\right)$$

Statistical analysis

Data were analyzed statistically for analysis of variance (ANOVA) following the method described by Gomez & Gomaz (1984) using SAS 9.2 package. The significance of difference among means was compared by using Least Significant Difference (LSD) and Duncan's Multiple Range Test (DMRT).

Table 3: Regression models for predicting developmental rate at different stages

Independent variables considered	Regression models	R^2
Stage-I : Emergence to flowering		
Maximum temperature (TMAX_f)	DR_{e_f}= 0.00274 +0.0048 TMAX_f	0.63
Minimum temperature (TMIN_f)	DR_{e_f}=0.0124 + 0.000241 TMIN_f	0.65
Day length (DL_f)	DR_{e_f}= -0.00166 +0.0015 DL_f	0.79
Multiple regression of all above variables	DR_{e_f}= 0.00636 – 0.000088 TMAX_f+ 0.00045 TMIN_f+0.00109 DL_f	0.97
Stage-II : Flowering to seed filling		
Maximum temperature (TMAX_sf)	DR_{f_sf}= 0.043 +0.00045 TMAX_sf	0.21
Minimum temperature (TMIN_sf)	DR_{f_sf}=0.049 + 0.00042 TMIN_sf	0.31
Day length (TMAX_sf)	DR_{f_sf}= 0.0269 +0.0023 DL_sf	0.28
Multiple regression of all above variables	$DRf_{\_sf}$= 0.01346 – 0.00029 TMAX_sf+ 0.00035 TMIN_sf +0.00310 DL_sf	0.47
Stage-III : Seed filling to maturity		
Maximum temperature (TMAX_m)	DR_{s_m}= -0.023 +0.0018 TMAX_m	0.67
Minimum temperature (TMIN_m)	DR_{s_m}=0.124 + 0.000241 TMIN_m	0.65
Day length (DL_m)	DR_{s_m}= 0.0253 +0.000017 GDD_m	0.18
Multiple regression	DR_{s_m}= -0.456 – 0.00061TMAX_m + 0.01035 TMIN_m +0.038 DL_m	0.76

DR_{e_f} = Developmental rate from emergence to flowering, $DR_{f\_sf=}$ Developmental rate from flowering to seed filling

$DR_{s\_m=}$ Developmental rate from seed filling to maturity

RESULTS AND DISCUSSION

Photo-thermal environment during crop growth period of four crop seasons

The photo-thermal environment of two crop seasons (2007-08 and 2008-09) at different phenological stages of the crop for four sowing dates are presented in Table-1. The pattern of average temperature was similar in both the years, average maximum temperatures ranged between 31.1 to 32.8 ^{O}C in first sown crop, then decreased during growth period of second (25.9 -28.6 ^{O}C) and third (27.7-29.8 ^{O}C) sown crop. During the growth period of fourth sowing, maximum, temperature again increased with the value ranged between 29.5-36.3 ^{O}C. Similar trend was observed in case of minimum temperature with the average values being 23.1-25.2, 15.1-16.4, 16.1-18.0 and 18.1-23.3 ^{O}C, during crop growth period of first, second, third and fourth sown crop, respectively. Though during vegetative phase of the fourth sown crop temperature was lower but from seed filling stage, temperature started to rise. The incoming solar radiation was lower during growth period of first (June) sown crop due to cloudy weather with the values ranged between 14.8 to 17.1 MJ m^{-2} day^{-1}. During crop growth period of second and third sown crop, solar radiation varied from 19.4-22.5 MJ m^{-2} day^{-1}. During reproductive phase of fourth sown crop, the solar radiation was higher (22.2-27.8 MJ m^{-2} day^{-1}). The average day length ranged from 11.1 hours in third sowing to 13.2 in case of first sowing. For both the years' first (June) sown crop received maximum rainfall due to south west monsoon with the values being 928 and 899 mm, in 2007-08 and 2008-09, respectively. Whereas, during growth period of other sowings, rainfall was erratic and meager.

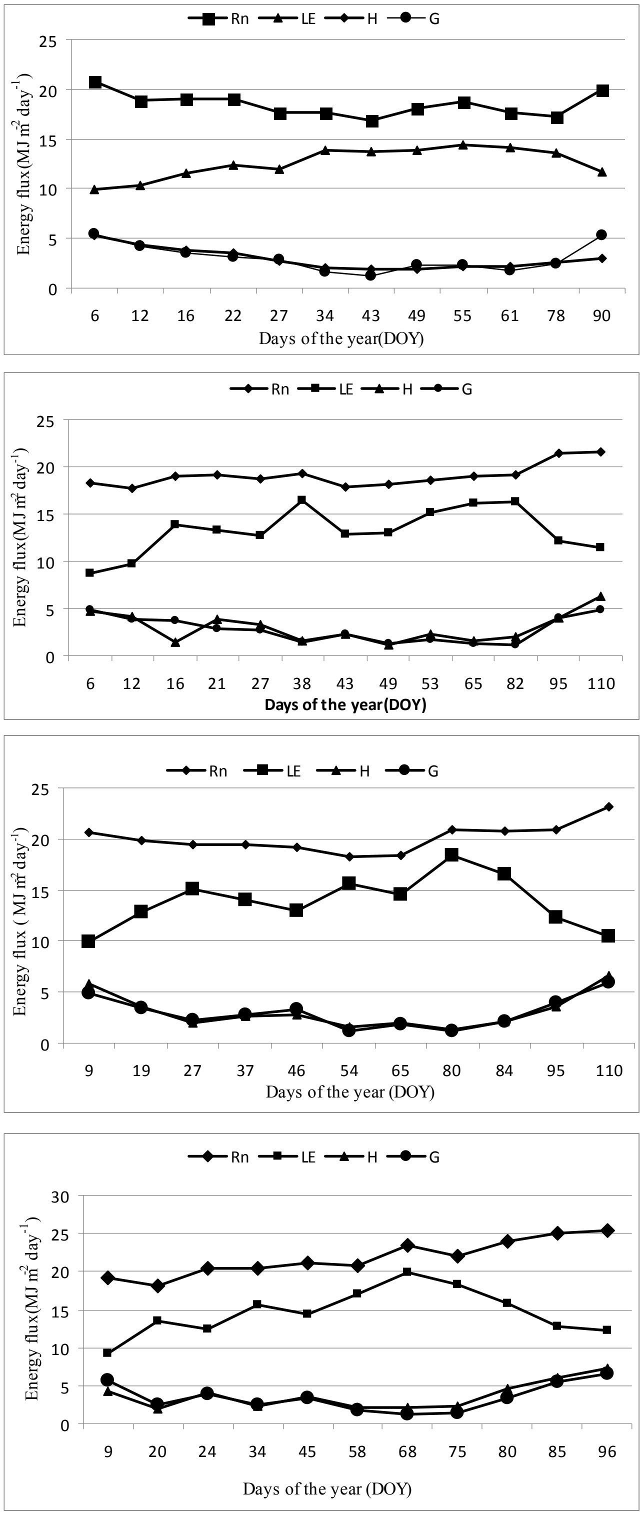

Fig.1: Energy balance of sunflower with five irrigations (pooled data of during 2007-08 and 2008-09)

S1- First sowing, S2-Second sowing, S3- Third sowing, S4- Fourth sowing

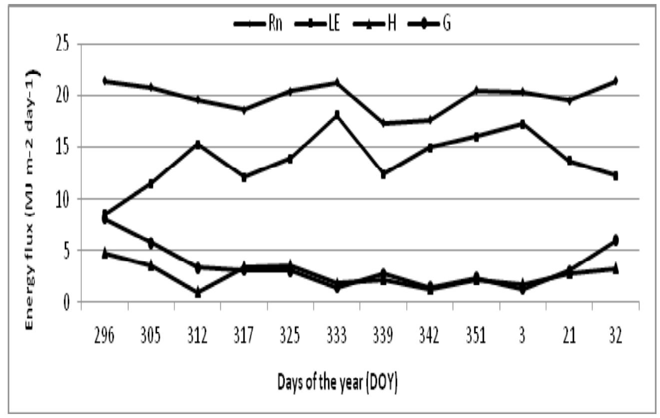

Fig.2: Evaporative fraction of sunflower with five irrigations during 2007-08

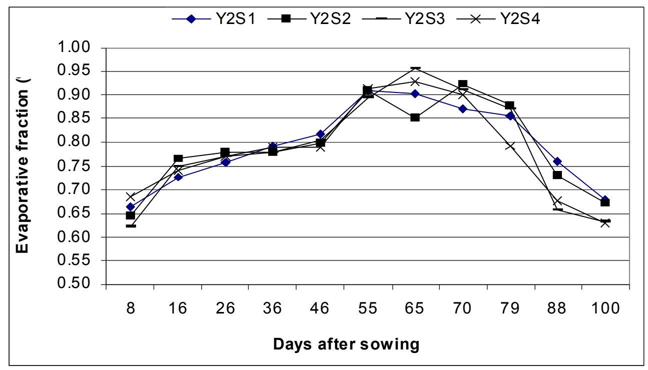

Fig.3: Evaporative fraction of sunflower with five irrigations during 2008-09

S1- First sowing, S2-Second sowing, S3- Third sowing, S4- Fourth sowing, Y1=Year 2007-08, Y2 =Year 2008-09

Phenological development rate and its relationship with photo-thermal environment

Effect of sowing dates on the duration of phenological developmental stages was found to be highly significant with similar trend in both the years (Table-2). First (June sown) crop took less days for flowering, seed filling and maturity with the days being 52.1, 66.9 and 96.5, respectively, which might be due to increased phenological development rate for existence of higher maximum and minimum temperatures during crop growth period. The similar trend was observed in case of fourth sown (S_4) crop. Maximum days for flowering (61.4 days), seed filling (79.5 days) and maturity (111.6 days) were taken by second sown crop (S_2) but these were statistically at par with third sown crop (S_3). The third sown crop (S_3) took 80.5 days to reach seed filling stage and it matured in 111.2 days. During the second (S_2) and third (S_3) sowings, the temperature was lower and the crop took more days to achieve all growth stages which might be attributed to slow phenological development rate of the crop during crop growth period. The different irrigation regimes had no significant effects on flowering and seed filling stages. But crop matured four days early under I_1 than that of I_3. Sowing dates and irrigations interaction had no significant (pd"0.05) effect on duration of phenological stages.

The relationship between phenological development rate (PDR) during different stages (emergence to 50% flowering, 50% flowering to 50% seed filling, 50% seed filling to maturity) and photo-thermal environment (maximum temperature, minimum temperature, day length) were established (Table-3). Data shows that the development rate was significantly correlated with maximum and minimum temperatures during emergence to flowering and seed filling to maturity stages of the crop. Day length was significantly correlated with vegetative phase of the crop but its effect on the PDR in reproductive stage was not evident.

Latent heat flux and surface energy balance

The seasonal variation of surface energy fluxes over sunflower crop stand during two crop growth seasons (2007-08 and 2008-09) were measured at 7-10 days interval and pooled data of mid day average values of 10.00-15.00 hour of two study years are depicted in Fig. 1. Net radiation (R_n), amount of energy available for physical or biological processes over the crop varied from 15.8 to 24.4 MJ m^{-2} day^{-1} in different sowing dates during two crop seasons.

The latent heat flux (LE) was found to be largely dependent of leaf area index (LAI) and soil moisture content and reached peak when LAI was maximum. The midday average latent heat flux (on clear days) varied from 9.7 to 14.72 MJ m^{-2} day^{-1} at different growth stages during June sown (S_1) crop. Whereas, in winter sown crop (S_2 and S_3), LE ranged between 8.55 to 16.50 MJ m^{-2} day^{-1} in different growth stages and years. In S_4 treatment LE varied from 8.70 to 19.11 MJ m^{-2} day^{-1}. The LE variation over the crop stand during different growing periods mainly occurred due to variation of solar radiation, temperature, vapor pressure deficit and soil moisture during the crop seasons. The LE by the crop increased immediately after application of irrigation water because of availability of soil moisture to evapotranspire.

The seasonal course of soil heat flux (G) of crop revealed that variation of 'G' during growth seasons clearly reflected the change of crop growth. The 'G' showed peak value during early vegetative and maturity periods when crop coverage was minimum and soil was dry. Afterwards, the course of 'G' was affected by development of crop canopy or leaf area index. Midday averaged 'G' value of crop stand ranged from 0.754 to 8.1 MJ m^{-2} day^{-1} at different growth stages and seasons and 'G' reduced drastically with the application of irrigation water. The ratio of G/R_n from maximum LAI to senescence stage was found to be 6.8-14.8 % over the crop. Soil heat flux showed declining trend during peak growth stage which coincided with maximum leaf area index (LAI) or maximum intercepted photosynthetically active radiation (IPAR). In general, where water did not limit the transpiration and when soil was wet, latent heat flux consumed most of the energy from net radiation. As the soil dried, water became less available for Evapotranspiration and the energy was utilized for heating the soil (soil heat flux) or heating the air (sensible heat flux).

Seasonal variation of evaporative fraction (EF) was computed and sown in Fig. 2 and 3 for the year 2008 and 2009, respectively. During peak growth stage (47-97DAS), ET consumed most of the energy, as a result evaporation fraction (EF) was higher during those days which ranged between 80-93% under different sowing dates in the first year and varied from 79-95% in different growth stages of second year.

CONCLUSIONS

High temperatures speed up the Phenological development of the crop and therefore, shorten growth duration for yield information. Crop duration and productivity were reduced when temperature increased during summer and rainy seasons. The day length was found to be influential at vegetative stage but no role was found reproductive phase of the crop. The latent heat flux (LE) was found to be largely dependant of leaf area index (LAI) and soil moisture content and attained peak when LAI was maximum. During peak growth stage, ET consumed most of the energy; as a result evaporation fraction (EF) was higher during those days.

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