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# Forecasting phenology of mustard crop in North-western Himalayas

**Ranbir Singh Rana[1], Bhosale Arjun Vaijinath[2], Sanjay Kumar[3] and Ranu Pathania[1]**

[1]Centre for Geo- Informatics Research and Training, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya , Palampur-176062 (H.P.), INDIA
[2]Chatrapati Shahu, Phule, Ambedkar College of Agriculture , Ashti, District Beed-414203 (Maharashtra), INDIA
[3]Department of Soil Science, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya , Palampur-176062 (H.P.), INDIA
*Corresponding author. E-mail:ranars66@rediffmail.com

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**Abstract:** Field experiments were conducted during *rabi* season of 2007-08 and 2008-09 to study the phenology, thermal indices and its subsequent effect on dry matter accumulation of mustard *(Brassica juncea* L.) varieties viz., RCC-4, Kranti and Varuna grown under varying environmental conditions of Himachal Pradesh. The early sown ($10^{th}$ October) crop varieties took maximum average growing degree days for flower initiation (492±1), 50% flowering (682±1), pod initiation (742±1), 90% pod formation (811±4) and maturity (1394±8) which decreased with subsequent delay in sowing time and recorded lowest under late sown ($9^{th}$ November) crop. The accumulated heliothermal units and photo-thermal units decreased from 9824 to 7467 $^{o}$C day hour and 19074 to 15579 $^{o}$C day hour, respectively. High heat-use efficiency was obtained under late sown condition on $30^{th}$ October. The heat-use efficiency (HUE) was high at 90% pod formation stage as compared to other stages in all the varieties and sowing dates (except $9^{th}$ November sowing). The early sown ($10^{th}$ October) crop had maximum calendar days and cumulative pan evaporation (158 days and 448.2 mm) followed by normal ($20^{th}$ and $30^{th}$ October) (153 days and 434 mm) and late ($9^{th}$ November) (138 days and 403.1 mm) sown crop indicating higher water requirement under early sowing. The predictive regression models explained 83-85% variation in dry matter yield in three varieties of mustard. The agro climatic indices are important determinants for temperature, radiations and photoperiods behaviors of crop. The accurate predictions of crop phenology are useful inputs for crop simulation modeling and crop management, and used for climate change assessment and simulated adaptations in present scenarios.

**Keywords:** Agro-climatic indices, Crop phenology prediction models, Mustard

## INTRODUCTION

In India oilseeds follow cereals sharing 14 % of the country's cropped area and accounting for nearly 3% GDP is the third largest rapeseed-mustard producer in the world (Anonymous, 2013a). The rapeseed-mustard in India contributes 12 % of the world yield and about 8.5% of the world's total rapeseed-mustard oil. (Anonymous, 2013b). In Himachal Pradesh, the rapeseed and mustard crop productivity is low (270 kg/ha) compared to national average yield due to low temperature during vegetative stage (Anonymous, 2013c). The study of crop phenology predictions are useful inputs for developing the simulated guided management practices through crop modeling in the face of climate change. Crop phenology can be used to specify the most appropriate stage of development process. Accurate prediction of crop phenology has widespread application in crop modeling and management (Adak *et al.,* 2009). Wurr *et al.* (2002) provided reviews on use of degree-days in plant development or thermal time in crop scheduling and prediction of crop maturity. Although the sequences of different phenological events are fixed within the lifecycle of a plant, the duration of particular stage of growth is directly proportional to temperature within a specified range. This duration for particular species could be predicted using the sum of daily air temperatures. Phenological development in mustard crop at Delhi conditions is also considered to be altered primarily by photoperiod, with a general shortening of phases as day length increases (Adak and Chakravarty, 2010).

Heat use efficiency (HUE) i.e., efficiency of utilization of heat in terms of dry matter accumulation depend on crop type, genetic factors and sowing time and has great practical application (Rao *et al.*, 1999). The quantification of heat use efficiency (HUE) is useful for the assessment of yield potential of a crop in different environment. The duration of each phenophase determines the accumulation and partitioning of dry matter in different organs. The cumulative pan evaporation is the best index for predicting the water requirement and duration of the phases from sowing to anthesis in wheat crop. Change in sowing dates leads to

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change in thermal environment of the crop with respect to different growth and development stages (Krishnamurthy and Bhatnagar, 1998). Therefore, the present study was undertaken to understand phenophase development in relation to various heat summation indices such as growing degree days (GDD), helio-thermal units (HTU), photo thermal units (PTU) and heat use efficiency (HUE) in three Indian mustard cultivars under different growing environments through change in sowing dates.

## MATERIALS AND METHODS

Field experiments were conducted at the research farm at the Department of Agronomy, Forages and Grassland Management, CSK Himachal Pradesh Krishi Vishvavidalaya, Palampur ($32^0 06^/$ N latitude and $76^0$ $03^/$ E longitude and altitude of 1290 m above mean sea level). Three recommended varieties of *Brassica juncea* viz., RCC-4**,** Kranti and Varuna were grown during two *rabi* seasons (2007-08 and 2008-09), following recommended agronomic practices under limited irrigated conditions. The varieties were sown on four different dates viz., 10, 20, 30 October and 9 November. The experiment was laid out in a randomized block design with three replications. The number of days required for attaining different phenological stages such as emergence, flower initiation, 50% flowering, pod initiation, 90% pod formation and physiological maturity were recorded. Weather parameters used for analysis were recorded at the agro-meteorological observatory which is located 60 meters from the experimental farm. In general, weather was normal during both the crop seasons (2007-08 and 2008-09). The mean maximum and minimum temperature for 2007-08 ranged from 11 to 31 $^0$C and 1.4 to 17 $^0$C, respectively and for 2008-09 it was from 16 to 28 $^0$C and 5 to 16 $^0$C, respectively. A total of 348 and 258 mm (523 mm normal rainfall of crop season) rainfall was recorded during the crop seasons for 2007-08 and 2008-09, respectively. Daily weather data of temperature (maximum and minimum), relative humidity, rainfall, wind speed, bright sunshine hours and evaporation were recorded for both growing seasons. These data were used to calculate:

**Growing degree days (GDD) ($^0$C day):** The growing degree days or heat units were calculated as per using base temperature of $5.0^0$ C (Nanda *et al*., 1996):

$GDD= [(T_{max}+T_{min})/2]-T_t$

Where, $T_{max}$= maximum temperature ($^0$C), $T_{min}$= minimum temperature ($^0$C) and $T_t$ = base or threshold temperature.

**Helio thermal units (HTU) ($^0$C day):** The product of GDD and corresponding actual sunshine hours for that day was computed on daily basis as:

HTU = GDD* actual sunshine hours

**Photo thermal units (PTU) ($^0$C day):** The product of growing degree days and corresponding day length for that day were computed on daily basis as:

PTU = GDD* day length

**Heat use efficiency (HUE):** To compare the relative performance of three different genotypes and treatments with respect to utilization of heat in terms of growing degree days during the crop growth period, heat use efficiency (HUE) as:

HUE (kg/ha/$^0$C day) =Accumulated biomass (kg/ha) / Accumulated heat units ($^0$C day)

**Correlation and Regression Studies:** Procedure Regression (Proc. reg.) program in SAS version 9.2 (SAS Institute, Cary, NC, USA) was used for developing regression equations between dry matter yield as dependent variable and thermal indices viz., GDD, PTU, HTU as independent variables for three different varieties of mustard. The two year data 2007-08 and 2008-09 were used for analysis for all planting windows. The correlation among different thermal indices (GDD, PTU and HTU), dry matter accumulation and cumulative pan evaporation were also calculated using the standard procedure.

## RESULTS AND DISCUSSION

**Assessment of heat summation indices:** During the present study phenophases of mustard crop were divided into six broad group's viz., sowing to complete emergence, emergence to flower initiation, emergence to 50% flowering, emergence to pod initiation, emergence to 90% pod formation and emergence to physiological maturity.

**Sowing to complete emergence:** Amongst all the varieties, the maximum growing degree days (Table 1) for completion of emergence from sowing were accrued by mustard crop sown on 30$^{th}$ October whereas the minimum accumulated growing degree days (AGDD) were taken by the crop sown on 10$^{th}$ October (Table 1). The values of AGDD for emergence varied between 100 and 125 for all dates averaged over varieties. Similarly, the HTU and PTU requirements for complete emergence were found to decrease as the sowing dates delayed up to 30$^{th}$ October. The differences observed were not much amongst varieties. However, amongst the sowing environments, high HUE was recorded maximum when the varieties were sown under delayed conditions i.e. on 9$^{th}$ November.

**Emergence to flower initiation:** For different sowing dates, thermal time requirement for flower initiation from emergence was the highest when sown on 10$^{th}$ October. The value of AGDD ranged between 393 to 493 degree day under different sowing environment and varieties. The varieties were similar in growing degree day requirements and the mean values were 493, 490 and 491 for RCC-4, Kranti and Varuna, respectively. For flower initiation, 10$^{th}$ October sowing required the maximum number of HTU and PTU, followed by 20$^{th}$ October sowing. The variations among the three cultivars for HTU and PTU were not signifi-

**Table 1.** Effect of sowing environments and varieties on Growing Degree Days (GDD), Photo-thermal Units (PTU), Helio-thermal Units (HTU) and Heat Use Efficiency (HUE) of Indian mustard (Pooled data of two years).

| Varieties/ Phenophase | Dates of Sowing | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10 October | | | | 20 October | | | | 30 October | | | | 9 November | | | |
| **RCC-4** | **GDD** | **HTU** | **PTU** | **HUE** | **GDD** | **HTU** | **PTU** | **HUE** | **GDD** | **HTU** | **PTU** | **HUE** | **GDD** | **HTU** | **PTU** | **HUE** |
| Emergence | 103 | 899 | 1128 | 0.07 | 106 | 1044 | 1166 | 0.07 | 121 | 1067 | 1331 | 0.06 | 109 | 937 | 1194 | 0.08 |
| Emergence to flower initiation | 493 | 4311 | 4930 | 0.70 | 456 | 3612 | 4560 | 0.75 | 427 | 3157 | 4265 | 0.85 | 396 | 2715 | 3955 | 0.90 |
| Emergence to 50% flowering | 681 | 5388 | 6873 | 2.55 | 639 | 4840 | 6449 | 3.30 | 620 | 4066 | 6257 | 4.40 | 613 | 3847 | 6192 | 4.70 |
| Emergence to pod initiation | 742 | 5911 | 7563 | 2.70 | 692 | 5006 | 7059 | 3.15 | 684 | 4409 | 6977 | 4.50 | 677 | 4283 | 6900 | 6.55 |
| Emergence to 90% pod formation | 814 | 6164 | 8466 | 4.45 | 759 | 5197 | 7889 | 5.55 | 762 | 5013 | 7925 | 6.10 | 804 | 5181 | 8362 | 5.90 |
| Maturity | 1403 | 9911 | 19074 | 2.30 | 1318 | 9112 | 17925 | 2.60 | 1264 | 8426 | 17190 | 2.70 | 1146 | 7467 | 15579 | 2.70 |
| **Kranti** | | | | | | | | | | | | | | | | |
| Emergence | 103 | 896 | 1128 | 0.07 | 98 | 961 | 1073 | 0.08 | 125 | 1102 | 1375 | 0.06 | 111 | 953 | 1216 | 0.08 |
| Emergence to flower initiation | 490 | 4280 | 4895 | 0.70 | 449 | 3550 | 4485 | 0.75 | 418 | 3096 | 4180 | 0.85 | 395 | 2710 | 3945 | 0.90 |
| Emergence to 50% flowering | 683 | 5411 | 6899 | 2.65 | 641 | 4862 | 6474 | 3.40 | 616 | 4043 | 6217 | 4.40 | 600 | 3768 | 6055 | 5.05 |
| Emergence to pod initiation | 740 | 5893 | 7543 | 2.60 | 700 | 5064 | 7135 | 3.20 | 674 | 4345 | 6875 | 4.75 | 674 | 4269 | 6875 | 6.40 |
| Emergence to 90% pod formation | 807 | 6107 | 8393 | 4.25 | 756 | 5171 | 7858 | 5.45 | 743 | 4885 | 7722 | 6.05 | 811 | 5225 | 8434 | 5.75 |
| Maturity | 1386 | 9793 | 18843 | 2.25 | 1341 | 9266 | 18231 | 2.50 | 1274 | 8495 | 17327 | 2.70 | 1150 | 7492 | 15634 | 2.60 |
| **Varuna** | | | | | | | | | | | | | | | | |
| Emergence | 105 | 915 | 1150 | 0.07 | 100 | 981 | 1095 | 0.08 | 121 | 1064 | 1331 | 0.07 | 107 | 923 | 1177 | 0.08 |
| Emergence to flower initiation | 491 | 4290 | 4905 | 0.70 | 454 | 3595 | 4540 | 0.80 | 414 | 3059 | 4135 | 0.85 | 394 | 2702 | 3935 | 1.00 |
| Emergence to 50% flowering | 680 | 5383 | 6868 | 2.65 | 645 | 4886 | 6510 | 3.40 | 618 | 4056 | 6237 | 4.25 | 608 | 3815 | 6141 | 5.00 |
| Emergence to pod initiation | 743 | 5918 | 7574 | 2.65 | 696 | 5035 | 7099 | 3.15 | 685 | 4414 | 6982 | 4.55 | 670 | 4242 | 6834 | 6.30 |
| Emergence to 90% pod formation | 816 | 6175 | 8482 | 4.25 | 760 | 5201 | 7899 | 5.20 | 757 | 4980 | 7873 | 5.85 | 814 | 5241 | 8461 | 5.65 |
| Maturity | 1390 | 9824 | 18904 | 2.35 | 1316 | 9094 | 17891 | 2.65 | 1270 | 8463 | 17265 | 2.65 | 1149 | 7489 | 15626 | 2.65 |

Where, GDD- Growing degree days, HTU- Helio-thermal units, PTU-Photo-thermal units, HUE – Heat Use Efficiency.

**Table 2.** GDD, PTU and HTU versus dry matter production based on different dates of sowing.

| Time of sowing | Thermal, photo and helio-thermal units | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RCC-4 | | | | Kranti | | | | Varuna | | | |
| | GDD | PTU | HTU | DM | GDD | PTU | HTU | DM | GDD | PTU | HTU | DM |
| 10 October | 1403 | 19074 | 9911 | 3203.3 | 1386 | 18843 | 9793 | 3105.6 | 1390 | 18904 | 9824 | 3176.7 |
| 20 October | 1318 | 17925 | 9112 | 3410.0 | 1341 | 18231 | 9266 | 3338.9 | 1316 | 17891 | 9094 | 3447.8 |
| 30 October | 1264 | 17190 | 8426 | 3405.0 | 1274 | 17327 | 8495 | 3392.2 | 1270 | 17265 | 8463 | 3312.8 |
| 9 November | 1146 | 15579 | 7467 | 3042.8 | 1150 | 15634 | 7492 | 2968.6 | 1149 | 15626 | 7489 | 3029.4 |

**Table 3.** Duration (days) of occurrence of phenological stages from sowing and cumulative pan evaporation under different sowing environments of Indian mustard (*Brassica juncea*) (Pooled data of two years).

| Phenophase | 10 October | | 20 October | | 30 October | | 9 November | |
|---|---|---|---|---|---|---|---|---|
| | Days | Pan Evapo-ration | Days | Pan Evap-oration | Days | Pan Evap-oration | Days | Pan Evap-oration |
| Emergence | 7.4 | 24.8 | 7.8 | 29.4 | 10.1 | 31.5 | 10.6 | 29.0 |
| Emergence to flower initiation | 51.4 | 146.8 | 52.7 | 141.9 | 61.2 | 150.9 | 69.5 | 163.7 |
| Emergence to 50% flowering | 67.5 | 189.4 | 71.4 | 184.4 | 81.0 | 195.0 | 91.0 | 215.5 |
| Emergence to pod initiation | 75.9 | 209.2 | 81.2 | 205.1 | 93.4 | 221.9 | 99.2 | 239.3 |
| Emergence to 90% pod formation | 88.7 | 236.3 | 93.0 | 232.2 | 103.7 | 247.4 | 111.0 | 286.8 |
| Emergence to maturity | 158.0 | 448.2 | 153.4 | 434.8 | 149.7 | 434.2 | 138.2 | 403.1 |

cant at 5 percent level 10th October sowing resulted in accumulating more growing degree days in short time due to high temperature and more sunshine hours, which resulted in early flowering. Similar results were also reported by Tripathi *et al.,* 2007 from HAU, Hisar for Indian Mustard. The heat use efficiency was high when the crop was sown on 9th November and low when sown on 10th October. Amongst the mustard varieties, RCC-4 of 6.55 kg/ha/$^0$C day recorded high HUE when sown on 9th November.

**Emergence to 50% flowering:** From emergence to 50% flowering stage cv. RCC-4, Kranti and Varuna accumulated 681, 683 and 680 GDD in early sown crop on October 10, respectively. The GDD decreased in all the varieties with delay in sowing from October 10 to November 9. Similarly, the HTU and PTU's were also high in 10th October sowing. RCC-4, Kranti and Varuna accumulated 5388, 5411 and 5383 HTUs and 6873, 6899 and 6869 PTUs, respectively. Among different sowing dates, high HUE was recorded when crop was sown on 9th November. The varieties Kranti and Varuna recorded high HUE as compared to RCC-4.

**Emergence to pod initiation:** In all the three varieties, the accumulated GDD accrued to reach pod initiation stage was found maximum in timely sown crop i.e. 10th October as compared to all other dates of sowing. cv. RCC-4, Kranti and Varuna accrued 742,740 and 743 GDD, respectively to attain pod initiation stage. High HTU and PTU were also accrued in early sown crop on 10th October. The varieties however did not differ significantly at 5% level of significance for GDD, HTU and PTU. The HUE increased with delay in sowing. The HUE was low in 10th October sowing irrespective of the varieties. The varieties, RCC-4 showed high HUE when sown on 9th November.

**Emergence to 90% pod formation:** In case of 90% pod formation phase, GDD requirements for mustard crop sown on different dates decreased as sowing dates delayed up to 30th October crop, whereas the crop sown on 9th November required more GDD due to increase in temperature in the later stages of crop growth. The HTU and PTU were in accordance with GDD. Among all the varieties, GDD, HTU and PTU were high in 10th October sowing (Table 1). The HUE was high in 30th October sown crop in RCC-4 (6.10), Kranti (6.05) and Varuna (5.85) as followed by 9th November, 20th October and 10th October. In general, at 90% pod formation stage high HUE was observed in comparison to other stages. This might be due to more accumulation of dry matter during this stage. Rana *et al.,* (2011) also observed that under similar environmental conditions with increase in temperature delayed sowing of mustard crop upto 30th October proved beneficial compared to early sowing.

**Emergence to physiological maturity:** The perusal of data revealed that for attaining physiological maturity, RCC-4, Kranti and Varuna accumulated 1403, 1386 and 1390 GDD, respectively in early sown crop on 10 October (Table 1). Accumulated GDD of mustard at harvest under different dates of sowing showed that the early sown crop availed more GDD to attain physiological maturity as compared to late sown crop. This may be due to high temperature at later part of growth that resulted in forced maturity of the crop. The accumulation of HTU was also reduced with delay in sowing which might be due to reduction in actual sunshine hours. These results are in accordance with Dhaliwal *et al*., 2007. who conducted research trials on raya oilseed crop under Ludhiana , Punjab conditions. The PTU also followed the similar trend as observed in GDD and HTU for sowing dates. The photo thermal units were also reduced with delay in sowing and this might be due to reduction in day length for late sown

**Table 4.** Correlation of thermal indices with dry matter and pan evaporation.

| Parameters | Dry matter accumulation | | |
|---|---|---|---|
| | RCC-4 | Kranti | Varuna |
| GDD | 0.73** | 0.72** | 0.74** |
| PTU | 0.64** | 0.63** | 0.65** |
| HTU | 0.65** | 0.64** | 0.66** |
| Pan evaporation | 0.74** | 0.74** | 0.78** |
| **Pan evaporation** | | | |
| GDD | 0.96** | 0.96** | 0.93** |
| PTU | 0.97** | 0.97** | 0.93** |
| HTU | 0.90** | 0.90** | 0.86** |

**Significant at P<0.01 (n=48) where GDD- Growing degree days, HTU- Helio-thermal units, PTU-Photo thermal units.

crop. Similar findings on accumulated PTU were reported by Dhaliwal *et al.*(2007) in raya crop variety PBR-91 at Ludhiana. In terms of HUE, all the varieties showed similar results. The HUE increased with the delay in sowing up to 30$^{th}$ October (6.10 in RCC-4, 6.05 in Kranti and 5.85 in Varuna) which might be due to favorable change in temperature. Kour *et al.* (2010) reported that the heat use efficiency increases with the advancement of the crop age up to milking stage and decreased later due to leaf senescence under temperate climate of Kashmir in rabi wheat crop.

**Phenological development under different sowing environment:** Thermal indices and dry matter in different sowing environment (Table 2) indicated that the early sown crop on 10$^{th}$ October accumulated the highest thermal indices (GDD, PTU, HTU) which subsequently decreased with delay in sowing in all varieties. Whereas corresponding to thermal indices the highest dry matter accumulation was obtained in 20$^{th}$ October sown crop followed by 30$^{th}$ October sown crop averaged over all varieties. The lowest dry matter and thermal indices were obtained in late sown crop.

**Duration of occurrence of phenological phases and Cumulative Pan Evaporation:** The data pertaining to days taken and pan evaporation of different phenological stages of mustard cultivars are presented in Table 3. The observations on phenological events reflected the influence of weather elements. Days taken from sowing to attain various growth stages viz., flower initiation, 50% flowering, pod initiation and 90% pod formation increased with successive delay in sowing from 10$^{th}$ October to 9$^{th}$ November.

On the contrary, days taken to arrive at physiological maturity reduced with each successive delayed sowings. Days taken for sowing to emergence were found similar for 10$^{th}$ and 20$^{th}$ October, and 30$^{th}$ and 9$^{th}$ November sown crop. Emergence took three days more due to low temperate condition in October and November sowing crop. Owing to higher maximum and minimum temperatures, the early sown crop (10$^{th}$ October) took lesser days to complete the vegetative and early reproductive phases than the late sown crop (9$^{th}$ November). However, the time of reproductive phase (end of seed filling and physiological maturity) was extended in 10$^{th}$ October sowing, as compared to later sown conditions. Similar results were reported by Roy *et al.,* (2005) for brassica crop varities viz. Varuna, Rahini and Jaikisan grown at Bharatpur , rajasthan, New Delhi and Mohanpur, West Bengal recorded higher yield in October sown crop. The sowing dates influenced the accumulated heat unit requirement to attain various phenological stages except the emergence stage. At maturity, high heat units were accumulated in 10$^{th}$ October sown crop, followed by 20 October, 30 October and 9 November, respectively (Table 1). Kaur *et al.,* (2006) had observed that the rate of development from emergence to anthesis of most of mustard crop species depends upon photoperiod as well as the temperature. Since the crop encountered high temperature and sunshine hours in 10 October sowing, the crop accumulated adequate heat units in shorter period thus resulting in early initiation of flowering. Early flowering in crop plants resulted in early siliqua development and increase in reproductive phase and ultimately the seed yield. Further, due to lower temperature during reproductive phase in 10 October sown crop, longer grain filling period was availed, which resulted in better pod and seed development. However, in case of delayed sown crop particularly in 9 November sowing the temperatures encountered by crop during vegetative phase and early reproductive phase were quite low but were higher during the later growth phase. Owing to these temporal temperature variations, the delayed initiation of flowering resulted in extended vegetative phase but shortened reproductive and maturity phases under delayed sowing conditions. These results are similar to those reported by Roy and Chakravarty (2007) for mustard crop under Delhi conditions having semiarid with dry hot summer and cold winters climate. The October sown crop recorded higher crop yield.

**Table 5.** Regression equations to predict dry matter at maturity using GDD, PTU and HTU in RCC-4, Kranti and Varuna varieties of mustard.

| Variety | Regression Equation | Estimated Dry matter yield (kg/ha) | Actual Dry matter yield (kg/ha) | Actual - Estimated Dry matter yield (kg/ha) |
|---|---|---|---|---|
| **RCC-4** | Y = -646.76 + 21.36GDD - 1.34HTU – 0.67PTU | 3369.8 | 3265.3 | -104.5 |
| **Kranti** | Y = -614.56 + 21.63GDD – 1.36HTU - 0.686PTU | 3312.8 | 3201.3 | -111.5 |
| **Varuna** | Y = -620.38 + 20.62 GDD – 1.29HTU – 0.65PTU | 3229.4 | 3241.7 | 12.3 |

Root Mean Square Error (RMSE): 88.5

The variation in cumulative pan evaporation was also observed under different sowing environments (Table 3). The early sown (10 October) crop showed maximum cumulative pan evaporation (448.2 mm) followed by normal (20 October, 30 October) and late sown (9 November) crops, requiring 13.4, 14.0 and 45.1 mm less water compared to early sown crop respectively. Prasad *et al.,* (2005) also reported that the early sown rabi wheat crop had maximum cumulative pan evaporation (664 mm) followed by normal (602 mm) and late (571 mm) sown crops under similar agro climatic conditions of Himachal Pradesh. Phenophase wise values of pan evaporation indicated that the water requirement of the crop around pod formation stage was the highest. Therefore, pod formation stage could be considered as a critical phase for the water requirement in mustard.

**Correlation and regression:** Accumulated GDD observed significant positive correlation at 5% level of significance with dry matter for varieties RCC-4, Kranti and Varuna with r value of 0.73, 0.72 and 0.74 (Table 4). The dry matter accumulation also showed positive and significant correlation with PTU and HTU for varieties RCC-4 (r = 0.64 and 0.65), Kranti (r = 0.63, 0.64) and Varuna (r = 0.65, 0.66). Within the crop growth period of *Brassica* species, dry biomass production was found to be significantly and positively correlated at 5 % level of significance with the accumulation of heat units (Miller *et al*., 1998; Merle *et al.,* 1997). Therefore, changes in thermal regimes would probably affect the physiological growth pattern of the crop, which in turn will affect the economic yield of the crop.

Thermal indices showed significant correlation with dry matter yield and their regression models revealed that $R^2$ values to the tune of 83 to 85% of total variation in dry matter yield for RCC-4, Kranti and Varuna under varied thermal regimes. However, the cumulative pan evaporation was not significant in regression analysis. Regression equations developed to predict dry matter of mustard using GDD, PTU and HTU in RCC-4, Kranti and Varuna are as under:

RCC-4: Y = -646.76 + 21.36GDD - 1.34HTU – 0.67PTU ($R^2$ = 0.83*)

Kranti: Y = -614.56 + 21.63GDD – 1.36HTU - 0.686PTU ($R^2$ = 0.84*)

Varuna: Y = -620.38 + 20.62 GDD – 1.29HTU – 0.65PTU ($R^2$ = 0.85*)

where, Y = Dry matter yield (kg/ha)

The verification of the regression equation revealed the minimal difference of 12.3 kg/ha between the estimated and actual dry matter yield in case of Varuna variety amongst the three varieties (Table 5). RMSE of 88.5 was observed between the estimated and actual dry matter yield. The estimated and actual values of dry matter yield for RCC-4, Kranti and Varuna varieties at different phenophases showed a close association indicating the significance of thermal indices to predict the dry matter production significantly.

The thermal indices viz., GDD, HTU and PTU for entire growth phases decreased with delayed sowing dates. Accumulated GDD of mustard at harvest showed that the early sown crop availed more growing degree days to attain physiological maturity as compared to late sown crop. The HUE to produce dry matter was highest in 30 October which indicated that delayed sowing are the best planting window in mid hill regions of HP. The correlation coefficients were significant and positive among GDD, HTU, PTU, and dry matter. The thermal indices viz., GDD, PTU and HTU were significant for predicting dry matter yield with regression models and account for 83 to 85% variation in dry matter yield prediction among different varieties of mustard.

## Conclusion

The results revealed that early sown ($10^{th}$ October) crop varieties took maximum average growing degree days for flower initiation, 50% flowering , pod initiation , 90% pod formation and maturity which decreased with subsequent delay in sowing time and recorded lowest under late sown ($9^{th}$ November) crop. The accumulated helio-thermal units and photothermal units also decreased with delay in sowing. High heat-use efficiency was obtained under late sown condition on $30^{th}$ October. The heat-use efficiency (HUE) was highest at 90% pod formation stage as compared to other stages in all the varieties and sowing dates (except $9^{th}$ November sowing). The higher water requirement under early sowing was observed. The study clearly indicated that sowing windows during October month recorded higher crop yield compared to November and delay in sowing of mustard crop under sub temperate climatic conditions. The predictive regression models explained 83-85% variation in dry matter yield in three varieties of mustard. The agro climatic indices are important determinants for temperature, radiations and photoperiods behaviours of crop. The accurate predictions of crop phenology are useful inputs for crop simulation modeling and crop management, and used for climate change assessment and simulated adaptations in present scenarios.

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