Phenology observation of Wheat(*Triticum Aestivum)* of five Indian winter wheat cultivars under different thermal growing conditions

Sanjay Anand

MS13110

A dissertation submitted for the partial fulfilment of BS-MS dual degree in Science

Indian Institute of Science Education and Research Mohali

April 2019

Certificate of Examination

This is to certify that the dissertation titled "Phenology observation of Wheat (*Triticum Aestivum)* of five Indian winter wheat cultivars under different thermal growing conditions" submitted by Mr. Sanjay Anand (Reg. No. MS13110) for the partial fulfilment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. Baerbel. Sinha (Supervisor) Dr. V. Sinha Dr. Ram Yadav

Dated: April 26, 2019

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Baerbel Sinha at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Sanjay Anand

(Candidate)

Dated: April 26, 2019

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Baerbel Sinha

(Supervisor)

Acknowledgment

I would like to express my sincere gratitude towards my supervisor Dr. Baerbel Sinha for letting me work with her and her kind support, guidance, motivation and the immense knowledge. Without her help and guidance, this project would not have been possible. I am very thankful to her for giving me this opportunity to work with her.Although being a long observational project her constant support throughout the whole time made it possible. Working with Dr. Baerbel Sinha has surely made me learn numerous amounts of different things. I would like to thank the rest of my thesis committee members Dr. Vinayak Sinha, and Dr. Ram Yadav

I would like to thank all the members of lab. Specially Shubham Tomar, Ashish, Sukhwinder, Pooja, Jitender, Ritika, Abhilasha for taking out their precious time to help me working on a bright sunny day andsharing words, and making things easier.These acknowledgements would beincomplete without mentioning some special ones. I would liketo thank Pranav Kukreti for his emotional support and to deal situations with positive thinking, long talks and Alkit for the discussions about football matches which made this journey at IISER Mohali memorable for rest of my life. Promit Moitra for his time and help to sort out every problem no matter what time is it. Ruchika Chahar and Himanshu who were always there for me to discuss about every possible topics we shared,worth mentioning Saurav Shekhar for sharing a part of this journey and all the philosophical talks, also Soumitra Mitra, Biswajeet Panda and Manauj too. Divanshu Gupta for sharing the football field and winning trophies with me, a true sportsman though.

I would like to thank Rhythm Shukla for her time and motivation. Always ready to help and understand my intuitions no matter what wrong steps i took. Thanks to her for being there with me in all my ups and downs, and also tolerate me in difficult times. I would really like to appreciate her to make this happen.

All may not be mentioned, but none is forgotten. Words may be due, but thoughts will remain with me.

To conclude above all, I thank my parents who have been there all these years for their unconditional support. I am truly grateful to have them by my side.

List of Figures

List of Tables

List of Photographs

Notation (Abbreviations)

SM Soil moisture.

VPD Vapour pressure deficit.

PAR Photosynthetic active radiation

CONTENTS

Abstract

This field experiment was conducted to evaluate the growth dynamics of wheat (*Triticum aestivum*) under different thermal growing coditions, at **Indian Institute of Science Education and Research, Mohali** campus. The wheat was sown with three thermal environments; early sown (T1: 1^{st} November), normal sown (T2: 15^{th} November) and late sown (T3: 1^{st} December) using five cultivars:PBW550, HD2687, RAJ3765, HD2967, WH1105,GW322, C306, DBW88 and two cultivars which were from local farmers. The study done for this experiment is carried out only for PBW550, HD2687, RAJ3765, HD2967 and WH1105. The experiment was laid out in three plot design with three replications for each cultivar. The data on different parameters, phenology, periodic growth, yield and yield attributes were recorded. During 1^{st} sowing that is 1^{st}November took more days to complete their life cycle as compared to that sown during 15^{th} November and 1^{st} December. Along with the cultivars, PAR interception was higher. Among the sowing dates, PAR interception, radiation and plant height were higher as compared to late sown crop which may be due to profuse vegetative growth. Among the yield attributes characters, early sown (1^{st} November) and normal sown (15^{th}November, 15^{th} December) wheat crop produced higher grain yield. There were significant effects on number of active tillers as HD2687 showed greater number of average tiller count as compared to other cultivars. The plant height was observed higher in cultivar HD2967 as compared to other cultivars.

Chapter 1

Introduction

1.1 Troposphere ozone

Tropospheric ozone impacts human health, agricultural crops and forest ecosystems worldwide. According to the tropospheric ozone assessment report, its levels have also increased and continue to rise particularly over Asia, over the last century. Tropospheric ozone (O3)is considered one of the most phytotoxic air pollutants. It affects productivity, growth, yield and quality of crops negatively and impacts the primary productivity of natural ecosystems.

It is well known that ozone damages food crops and natural vegetation.O3 in the troposphere is a photochemical air pollutant. This means it is a secondary pollutant formed in the presence of sunlight from pollutants such as NOx and VOC's. It is believed that globally O3 causes more damage to vegetation than other pollutants, such as SO_2 and NOx which can cause acid rain and particulate matter which can shield leaves from radiation combined.

It is not emitted directly into the atmosphere but is produced by reactions requiring sunlight, nitrogen oxides, and volatile organic compounds. NOx emissions are caused by all forms of combustions i.e. vehicles, industries and power plants as high temperatures in a flame dissociate atmospheric N_2 molecules and produce NO. VOC's are emitted both naturally, from plants and from anthropogenic sources such as solvent use and combustion processes.

Unlike primary pollutants such as CO, NOx, NH_3 or SO_2, which are directly emitted ozone is a secondary pollutant formed in the ambient air through a complex set of sunlight-initiated reactions of its precursors, primary emissions of NO_x (NO_2+NO) and volatile organic compounds (VOC). The term VOC encompasses all organics (e.g., hydrocarbons, alcohols, aldehydes, sulphur and nitrogen -containing organics, etc.).

1.2 Ozone effects on plants

The influence of ozone on vegetation is dependent on theozone dose. Each plant species has a phytotoxic ozone dose. When the flux into the plant expressed in the units of mol per square meter of active leaf surface area in a given time frame exceeds the threshold that the plants detoxifying system is capable of handling the plant is damaged (Pleijel et al., 1991; Heath,2008; Iriti and Faoro, 2009).Ozone enters leaves throughplant stomata during normal gas exchange. Most gas exchange happends during daylighthours for the purpose of photosynthesis. Once inside the plant it can damage the leaf tissue, inhibit photosynthesis orimpair plant metabolism. This can result in yield reductionin agricultural crops (Wilkinson et al., 2012; Ainsworthet al., 2012; Leisner and Ainsworth, 2012).

Some plants have been reported to respond to ozone stress by reducing their stomatal aperture (Torsethaugen et al., 1999; Heath,2008; Iriti and Faoro, 2009; Ainsworth et al., 2012). While this may prevent ozone from entering, it also reduces the amount of photosynthesis that can happen. Picchi et al. (2010) reported thatfor different wheat cultivars with higher leaf damage showed larger yields under high ozone while those with less visible leaf damage showed large yields reductions due to ozone. This seems to suggest that visible damage and premature death of some of the leaf tissue may not be a good proxy for crop yield loss.

The effect of ozone decrease the primary metabolism in fixation of CO2, change in rubisco content and other component of the photosynthetic machinery and Calvin benzo cycle enzyme including rubisco activase, ATP synthase, the hydrogen evolving subunit of photo system second. The decrease in primary metabolism intend to decrease the area of leaf because change in enzyme activity decreases the starch and sucrose level.

1.3 Wheat as a winter crop

Wheat is a cool season cereal food crop. In India it is as a major cereal crop that ranks second after rice with respect to area and production. Wheat requires cool weather for its early growth. Wheat is a popular crop due to its high adaptability to different environmental conditions. Wheat also has a high yield potential. One of its proteins, gluten, gives wheat visco-elastic properties that allow dough to be processed into pasta, noodles breadand other food products.

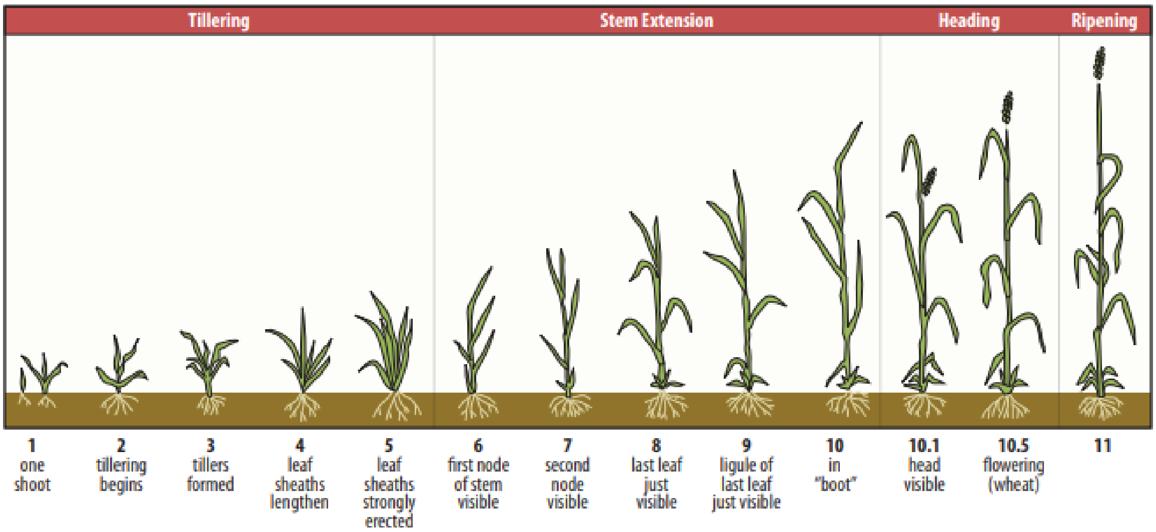


Figure 1: Growth stages for wheat showing tillering, stem extension period, heading stage and the ripening stage (Reproduced with the kind permission of the author Carrie A. Knott, Plant and Soil Sciences from ID-125, A Comprehensive Guide to Wheat Management in Kentucky).

Toensure maximum yield potential wheat plants need to have sufficient tillers prior to winter dormancy. Wheat begins to actively grow, "breaking" dormancy. The first nitrogen application after the initial application during sowing timeis recommended at this stage. Through observations leaves often appear to be twisting spirally and the plants will be growing along the soil surface initially. Once the wheat has elongated they become erect. The growing point continues to be below the soil surface at that point in time. Once theflag leafis visible it must be protected at all cost, although many chemicals can no longer be applied after that point. Since this leaf receives least shading, almost all (75%-80%) of a wheat plants photosynthesis (energy to fuel grain fill) occurs in the flag leaf. Once the wheat head has completely emerged, the beginning offlowering takes place within a week.When the first anthers become visible roughly one to two weeks after the head has emerged, most flowers are already fertilized as wheat is self-pollinating. Newly emerged anthers are bright yellow and they become paler until they are white with time. Flowering begins in the middle of the head and progresses towards both ends of the head.

1.5 Crop yield losses over the IGP and definition of the problem and targeted improvements through this study

Punjab is one of the major agricultural producers in the country, therefore crop yield losses due to environmental pollution is a serious concern as it already have much environmental pollution due to biomass burning and other anthropogenic activities (Sarkar, Kumar, & Sinha, 2013). One of the tropospheric pollutant, which causes crop yield loss known to be Ozone. Ozone is formed in the troposphere in the presence of the sunlight, when NOX, VOCs and CO react with each other (V. Sinha, Kumar, & Sarkar, 2014). These precursors to Ozone are formed due to the combustion of fuels and biomass, so in general if there is more environmental pollution then there will be higher concentration of Ozone in the presence of the sunlight.

Ozone during the daytime hours when the stomatal conductance is higher, at the same time concentration of the Ozone also hits its peak values. Therefore, when the plant stomata are open Ozone is taken up by the stomata along with the other gases present in the atmosphere. Once Ozone enters inside the stomata it, damages the mesophyll cells of the plant leaf (Sutinen, 1987). These mesophyll cells are the one which carry out most of the photosynthesis in the plant leaf. Once these cells are damaged due to the ozone injury plant become less efficient in carrying out the photosynthesis, as a result low crop yield is obtained. Response to different environmental condition varies from cultivar to cultivar. Some cultivars show drought resistance, some are better at tolerating the heat stress, some show anti-oxidative properties as a defense against Ozone (Feng, Wang, Pleijel, Zhu, & Kobayashi, 2016). Cultivars which keep their stomata open during the period when conditions are dry and hot are more prone to the damage by ozone, because hot and dry conditions are the conditions when the concentration of the ozone is higher. Some cultivars do the opposite; they close their stomata when the conditions are dry and hot. But other things also have to be considered for making such judgement, such as how is the phenology function behaving for the cultivar, some cultivars are more prone to heat stress towards the end of growing season (grain filling stage)(Farooq, Bramley, Palta, & Siddique, 2011).

This study will help to find the cultivars which are suitable for different types of environmental conditions, and are good at coping with different environmental stress and air pollution without having significant adverse effect on the plant yield.

Chapter 2

Materials and Methods

2.1 Location and Climate

Experimental site is located in Indian Institute of Science Education and Research (IISER), Mohali campus (30˚39'51.54 N 76˚43'55.65 E) which falls in winter dry steppe climate zone. Site is located in a suburban setting. As this region of country is densely populated due to its fertile land and the major occupation of people is agriculture, horticulture, and animal husbandry. Being the reason Punjab has its fare share in agriculture produce.

The topography of Mohali is even. It is mostly a plain of alluvial type. The land used for agriculture also has loam to heavy loam and sand to sandy loam soils and has high water holding capacity. The land is also rich in nutrients and is best suitable for crops like wheat, maize, paddy.

The climate of Mohali region is winter dry, has a hot summer and a moderately cold winter. The period from about middle of November to February is the cold season however, freezing does not happen. Rainfall is limited to periods with Western disturbances. Summer season usually starts rapidly from some point in March and ends in June or July with the arrival of the monsoon. The south-west monsoon season commences late in June and continues up to about middle of September. This period brings maximum rainfall. The period from mid-September to the middle of November constitutes the post monsoon season. Wheat sowing happens during the second part of the post-mosoon season and harvest happens shortly after the onset of summer. The temperature ranges from minimum of 4ºC in winter to 45ºC in summer.

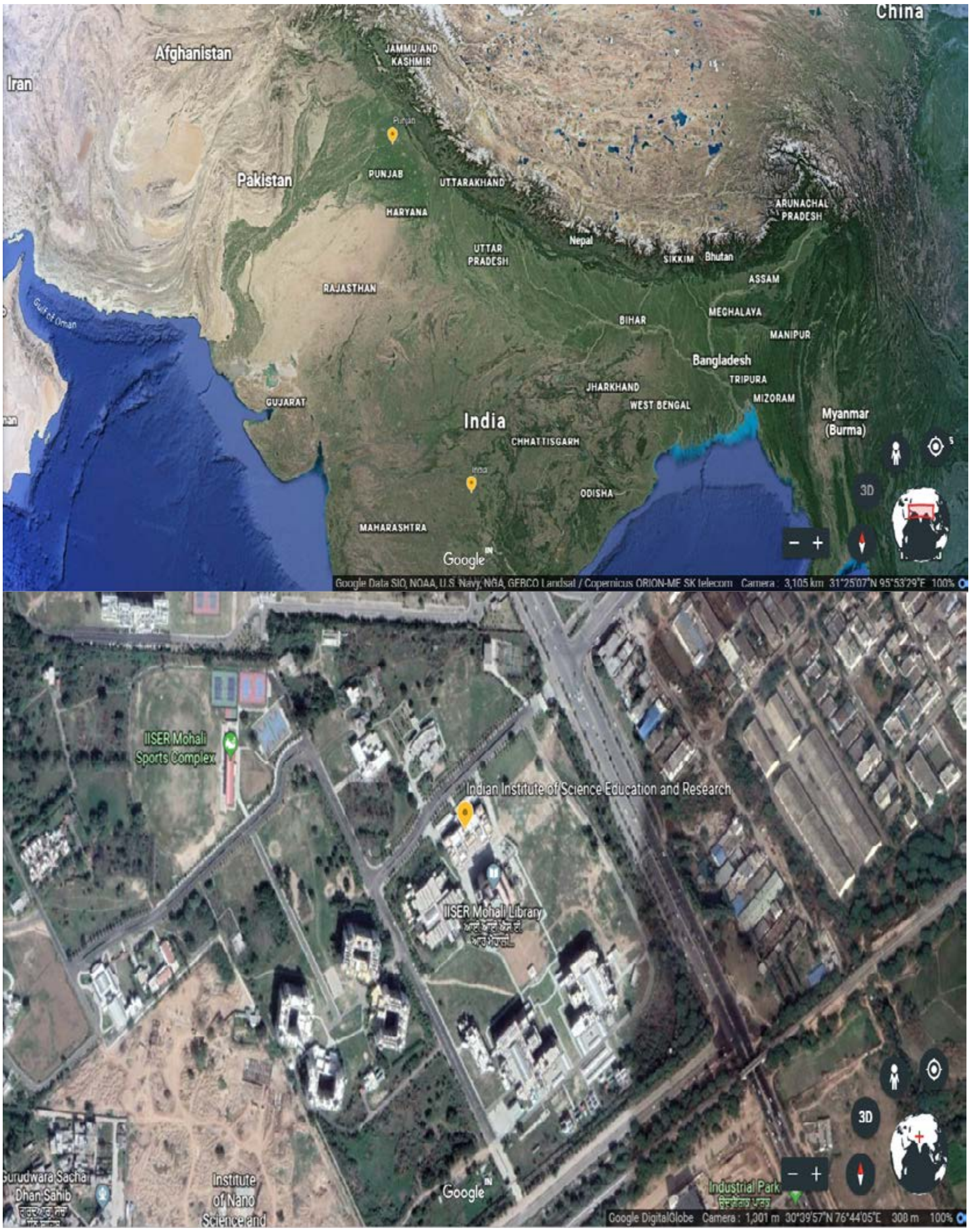


Figure 2: Location of Mohali in the Indian subcontinent, IISER campus and location of Experimental field within the campus.Image ©2018 Google.

2.2 Agricultural methodologies

2.2.1 Preparing the Experimental Field

Starting with the soil, before initiating ploughing up of sod, it is important to know the type of soil to work with. The process starts by testing of soil which enables us to improve it and amend it as needed for growing the best crops. The first steps to prepare the land for planting involve looking at soil texture and fertility and adjusting it as needed. The well prepared land before sowing also helps in obtaining a good water shedding and drainage for the uniform irrigation throughout the field. The land was watered before doing any tilling, water was kept standing in the field for 3-4 days. After the land was squashy enough to pull out the standing weed out of the soil, then a harrowing tool was used to get some consistency and making the land dry faster. A tractor rotavator worked through the field for obtaining even more consistency in the soil texture throughout the field .Installation of mesh fence was also done manually so as to protect the field from various native animals (rabbits, dogs, squirrels). Planting basins were prepared according to the predefined plan for planting and irrigation as shown in Fig 3.

Sowing was also carried out as per the plan shown in Fig 3. This experiment concluded three plots each having three columns of ten cultivars each. Buffer plantation was done with the help of cultivars from local farmers. The irrigation channel run through the field and was repeated after every 30 days respectively. Sowing was done with an iron rod making hole of 4cm of depth.

Following are some details regarding the sowing date for the three plots:

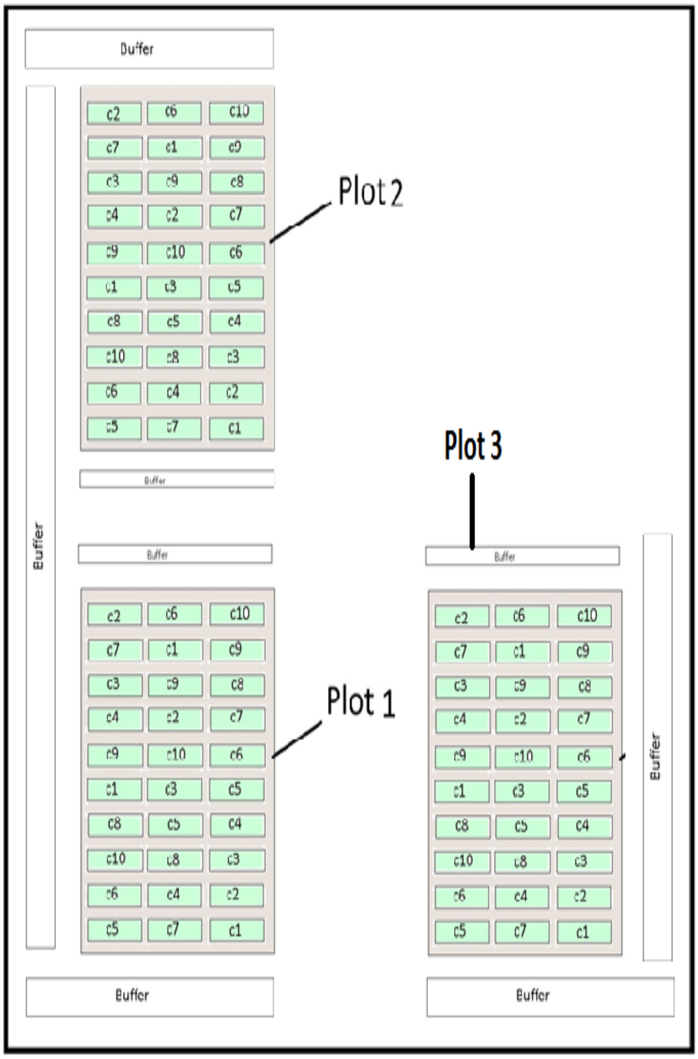
- 1st sowing done for plot-1 1/11/2018
- 2nd sowing done for plot-2 15/11/2018
- 3rd sowing done for plot-3 1/12/2018

Field measurements and sowing:

- Dimension of the experimental field = 25m*20m
- Total number of cultivars = 10
- Rows of each cultivar = 3

- Distance between each rows = 23cm
- Depth of holes for sowing = 4cm
- Number of seeds per hole = 2
- Plant to plant distance = 15cm
- Cultivar to cultivar distance = 44cm

Seeds sown in each hole were two as a precautionary measure for ensuring emergence from every hole. Proceeding further, holes with more than one emergence were singled out of smaller (unhealthy/unfit) plants and weeding was also done manually after waiting for a few regular intervals of days.



C1 = PBW550

C2 = HD2687

C3 = RAJ3765

C4 = HD2967

C5 = WH1105

C6 = GW322

C7 = C306

C8 = DBW88

C9 & C10 = From local farmers

Figure 3: Layout of the experimental field.

Photograph 1: Plot1 (sowing done on 1/11/2018) and Plot2 (sowing done on 15/11/2018).

2.2.2Fertilizer application

Fertilizers were also implemented on the respective plots:

- Mono-Ammonium Phosphate(MAO-12:61:00)
- Potassium Nitrate(NOP-13:00:45)
- Calcium Nitrate(100% Water Soluble Fertilizers)
- Micronutrients were also applied twice on the respective fields.

These fertilizers were applied to all the three plots on the following date:

- 22/11/2018
- 5/12/2018
- 18/12/2018
- 28/12/2018

2.3 Types of cultivars to study for the experiment

1. **PBW550(C1)**
2. **HD2687(C2)**
3. **RAJ3765(C3)**
4. **HD2967(C4)**
5. **WH1105(C5)**

PBW550(C1), HD2687(C2), HD2967(C4), WH1105(C5) are the four cultivars which are associated to the area of **Punjab**and **Haryana** region of the country. And whereas RAJ3765(C3) is associated to the north west region of the country. The above listed cultivars are briefed as follows:

1. **PBW550(C1):** Double dwarf variety with a reported plant height of 86 cm. In our experiment the height was 89 cm, 90 cm and 85 cm for a sowing on 1st of November, 15th of November and 1stof December, respectively. The ears are medium dense, tapering in shape and fully bearded with white smooth glumes. Its grains are bold, amber, hard and lustrous. PBW550 is resistant to yellow and brown rusts. The maturity stage begins in about 146 days. Sowing of this is recommended from 2nd week of November.
2. **HD2687 (C2):**. Commonly known as 'Shreshta'. It was developed in IARI (1999). It is suited for timely sown and irrigated condition. This variety supposedly takes 132-136 days to reach maturity, however it was the last to reach the flag leaf stage after which hardly any observations are available. Still it is clear that the plant progressed much slower than PBW550 and therefore probably reached maturity later or at a comparable time to PBW550 and HD2967. HD2687 is bred for resistance against stem rust and kernel bunt pathotypes. This variety is good for chapati making and has high protein content.
3. **RAJ3765 (C3):** This variety grows up to plant height of 80-90 cm. It takes about early 126-134 days to reach maturity. RAJ3765 is susceptible to black rust,yellow rust, and brown rust. Also favoured for making chapatti, bread, and biscuit.
4. **HD2967 (C4):** This is double dwarf variety with an reported average plant height of 101 cm. In our experiment the height was 101 cm, 103 cm and 92 cm for a sowing on 1st of November, 15th of November and 1st of December, respectively.It is known for profuse tillering, although in our experiment

PBW550 and HD2687 had a similar or greater number of tillers. The ears are medium dense and tapering in shape with white glumes. The grains are amber, medium bold, hard and lustrous. HD2967(C4) is resistant to yellow and brown rusts but susceptible to kernel bunt and loose smut diseases. It takes about 157 days to reach maturity.

5. **WH1105(C5):** This variety was developed by HAU Hissar, also available at Rauni (Patiala). WH1105(C5) is suitable for irrigated and timely sown conditions. Plants take 145 days to mature with height of 95-100cms. WH1105 are not only high-yielding varieties, but are also lesser prone to yellow rust.

We have used the methods detailed above for sowing of the five cultivars mentioned and have then recorded data to measure growth at various stages of the cultivars. Data was taken at three different points of time; **emergence** - ~5 days after sowing, **flagleaf** - ~55 days after sowing and **anthesis** – 80 days after sowing. The observables recorded are detailed in the next chapter.

The crops are harvested after they reach full maturity, which is decided by observing the color of the wheat plant.

2.4 Meteorological data

To study the correlation between fractional growth and the temperature in the field, we have recorded the temperature hourly every day during the sowing and growth period of the cultivars. We have used the EM50 data logger device linked to multiple sensors which measure temperature, soil moisture, relative humidity (RH), barometric pressure, photosynthetic active radiation, wind speed and wind direction.The Decagon meteorological station was setup in the wheat field and measured at crop height.Some of themeasures taken for study are as:

- Soil Moisture
- Temperature and RH sensor with radiation shield
- Wind speed and wind direction sensor
- Barometric pressure sensor
- Sensor for photosynthetic active radiation (PAR)

Photograph 2 : The DecagonEM50 device set up in the experimental field.

Chapter 3

Results and Discussion

The prime objective of the present study was to quantify the contribution of changes in sowing dates and thermal conditions to the changes in phenology of winter wheat. This is an in-situ experiment conducted within the campus of IISER MOHALI.

3.1 Specific meteorological conditions during the 2018-2019 wheat growing season

Figure 4 shows the Temperature, PAR, Relative Humidity, Wind speed, and SM, VPD for the growing season 2018-2019.The minimum temperature of 2.4 ^{0}C was observed on 24th December at 07:00 hours after 57 DAS and the maximum temperature around 37.5^{0}C was observed in the end of growing season during day light hours around 13:00-13:30 hours on 10th of April when the crops were already matured. For the growing season 2018-2019 there is a continuous increase in the temperature from march to end of the growing season. Till march the temperature fluctuates between 10-25^{0}C. There is an increase in VPD towards end of growing season which indicates drying conditions.

Figure 5 shows the diel and whisker plot for PAR, Temperature, Wind speed, and VPD and. It is clearly visible from the graphs below that everyday sun rises around 07:00 AM and the temperature starts rising after 1 hour. Solar radiation is high around 12:00 PM. Wind speed is maximum at 14:00 hour and at the same time VPD is also higher around this time.

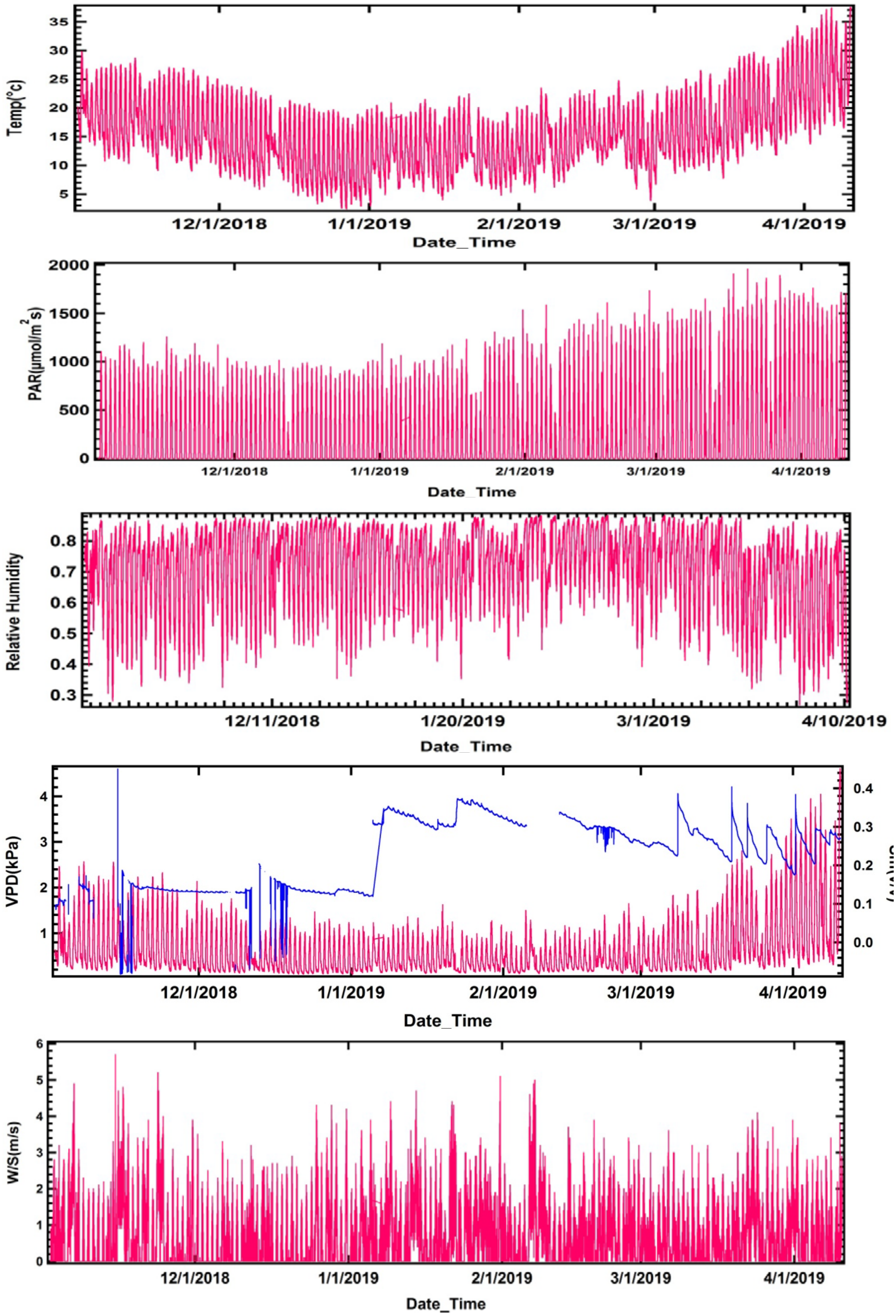


Figure 4: Temperature, PAR , Relative Humidity, Wind speed, and SM, VPD for the growing season 2018-2019.

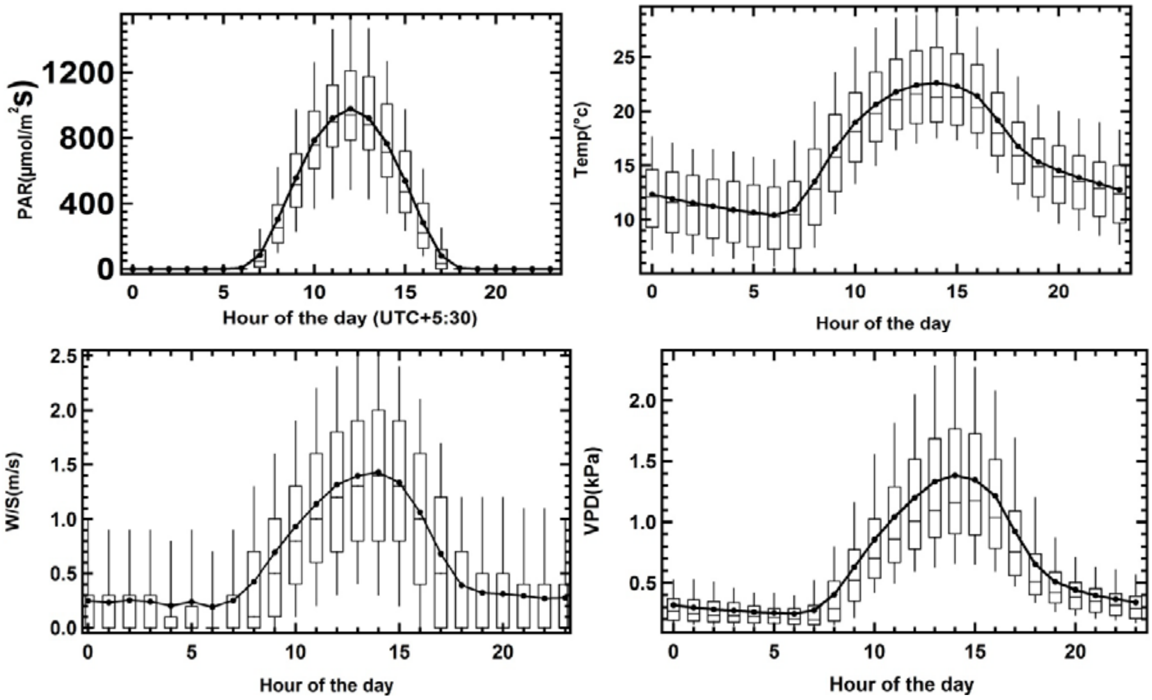


Figure 5: Diel box and whisker plot for PAR, Temperature, Wind Speed and VPD for the growing season 2018-2019. All measurements taken during a certain hour of the day during the entire growing season are binned against the start time of the hour. The lower and upper limit of the box represents 75th and 25th percentile and the line in the middle represents the median and the average is marked by a dot. The Whiskers show the90th and 10th percentile of the data.

3.2 Crop growth and development

After careful observation of all cultivars, the count for different stages of growth as **Emergence, Flag leaf, Heading, Anthesis** were done manually.

- **Emergenc**e: At this stage, requisite moisture and temperature are required for the seeds to reach emergence. With favorable conditions, seedling emerges within six to eight days. Until the first leaf becomes serviceable or functional, the seedling depends upon the nutrients and energy stored in seed.

Photograph 3: Emergence post 9 days of sowing

Photograph 4: Flag leaf post 63 days of sowing.

- **Flag leaf:** For the development of wheat plant this stage is considered as a critical one. The final leaf emergence is known as the flag leaf, and is crucial for attaining the high grain yields. It is at flag leaf stage we need to be careful in order to avoid damage and also inspect about certain infection to leaf once it emerges.

- **Heading:** After forming the tillers, followed by stem extension or elongation of the internodes take place and the head initiates to grow inside the flag leaf. When fifty percent (50%) of the spikes comes out then the count for heading is started.

Photograph 5: Heading post 63 days of sowing.

- **Anthesis:** This is the flowering period of plant. The flowering can be seen at the spikelet from where the anthers tend to bulge out or extrude. This stage is very crucial and also needs observation time to time.

Photograph 6: Anthesis post 98 days of sowing.

- **Pre harvest matured plant:** The crops were now ready to harvest. At the stage when plant attains golden bright color and the grain filling has been completed, the wheat crop gets ready to harvest.

Photograph 7: Pre- harvest matured plant post 151 days after sowing.

3.3 Observations

We carried out number counts for the three stages of the five cultivars **PBW550(C1), HD2687(C2), RAJ3765(C3), HD2967(C4),** and **WH1105(C5)**. After **emergence**, we selected the healthiest plant out of the two seeds that were sowed in each hole, giving us 30 plants for each cultivar. The unfit or rejected plant was uprooted. Number counts were then carried out for the next three stages, i.e. **Flag leaf, Heading,** and **Anthesis**. This observation routine was carried out for all the three plots at the experimental field. The data recorded are shown in Table 1.

3.3.1 Emergence

Table 1 : Emergence data recorded for **PBW550(C1), HD2687(C2), RAJ3765(C3), HD2967(C4),** and **WH1105(C5).**

PBW550(C1)

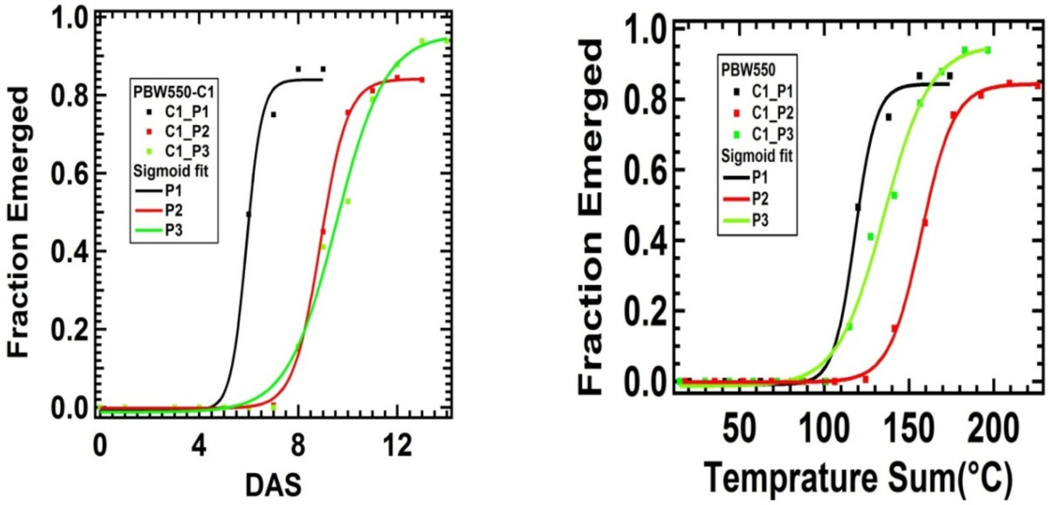


Figure 6: Emergence count as a function of Days after Sowing (**DAS**) and Thermal Sum for **PBW550(C1).**

Figure 6 shows us the emergence count fraction of **PBW550 (C1)** for all the different sowing dates. The left hand side shows the emergence count as a function of Days after Sowing (DAS), and the right hand side about emergence count as a function of Thermal sum. The y-axis shows the fraction of 180 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

PBW550 takes 6 days to reach 50% of emergence for 1st sowing, around 9 days for 2nd sowing, and 10 days for the 3rd sowing. This can also interpreted from the different temperatures required for emergence growth. As 1st sowing has a low temperature sum as compared to the other two and has slight contrast for the date of emergence followed by the different sowing dates.

HD2687 (C2) :

Figure 7 shows us the emergence count fraction of **HD2687(C2)** for all the different sowing dates. The left hand side shows the emergence count as a function of Days after Sowing (DAS), and the right hand side about emergence count as a function of Thermal sum. The y-axis shows the fraction of 180 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

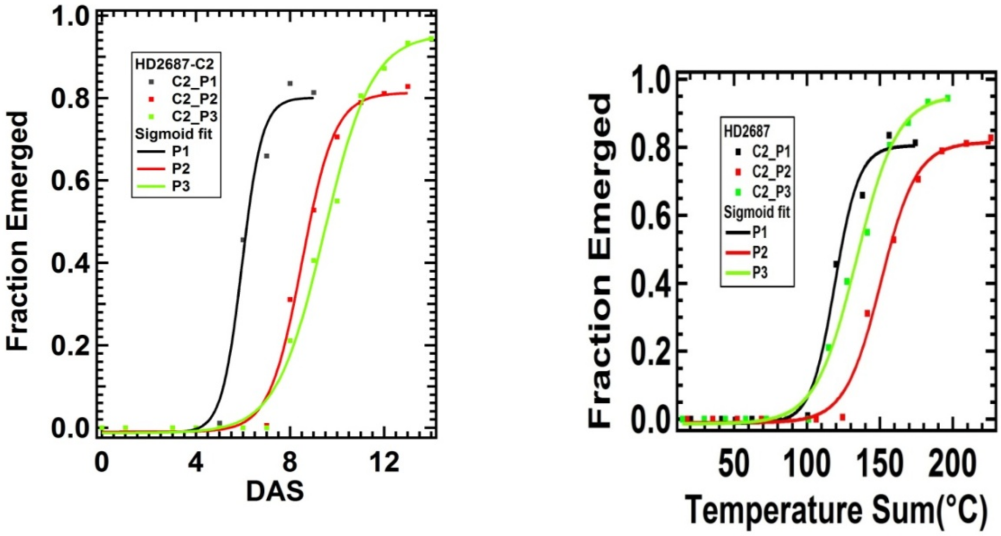


Figure 7: Emergence count as a function of Days after Sowing (**DAS**) and Thermal Sum for **HD2687(C2).**

HD2687 alsotakes 6 days to reach 50% of emergence for 1st sowing, around 9 days for 2nd sowing, and 10 days for the 3rd sowing. From the temperature sum figure it is known that there is a gradual increase for 2nd sowing and the temperature is getting low for 3rd sowing required for emergence growth. As 1st sowing has a low temperature sum as compared to the other two.

RAJ3765 (C3) :

Figure 8 shows us the emergence count fraction of **RAJ3765(C3)** for all the different sowing dates. The left hand side shows the emergence count as a function of Days after Sowing (DAS), and the right hand side about emergence count as a function of Thermal sum. The y-axis shows the fraction of 180 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

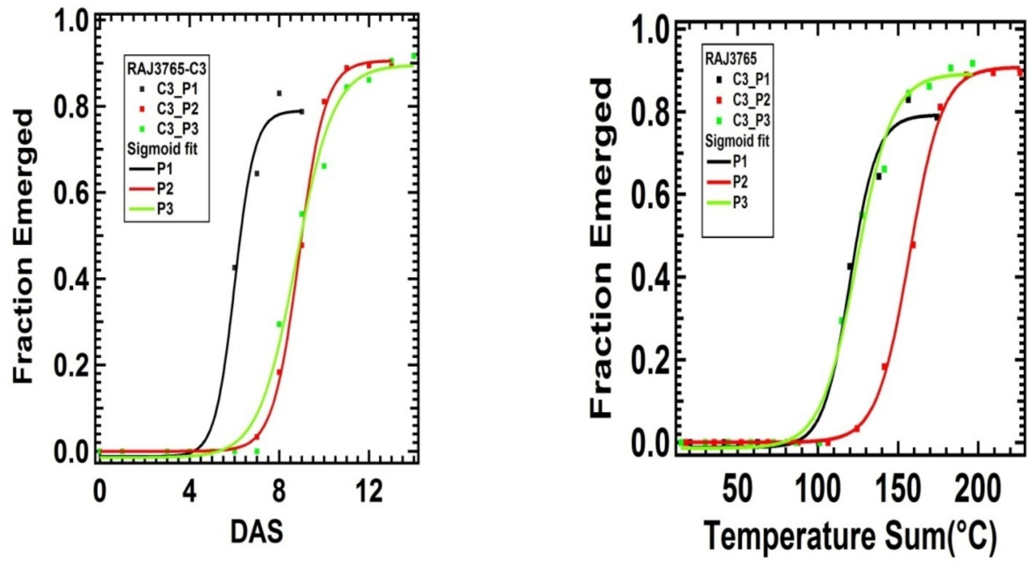


Figure 8: Emergence count as a function of Days after Sowing (**DAS**) and Thermal Sum for **RAJ3765(C3).**

RAJ3765 took 6 days to reach 50% of emergence for 1st sowing, around 9 days for 2nd sowing, and 9 days for the 3rd sowing. The temperature sum figure shows that there is increase in temperature sum reaching to 150^{o}c for 2nd sowing and then temperature is getting low for 3rd sowing reaching somewhat near to the 1st sowing.

HD2967(C4) :

Figure 9 shows us the emergence count fraction of **HD2967(C4)** for all the different sowing dates. The left hand side shows the emergence count as a function of Days after Sowing (DAS), and the right hand side about emergence count as a function of Thermal sum. The y-axis shows the fraction of 180 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

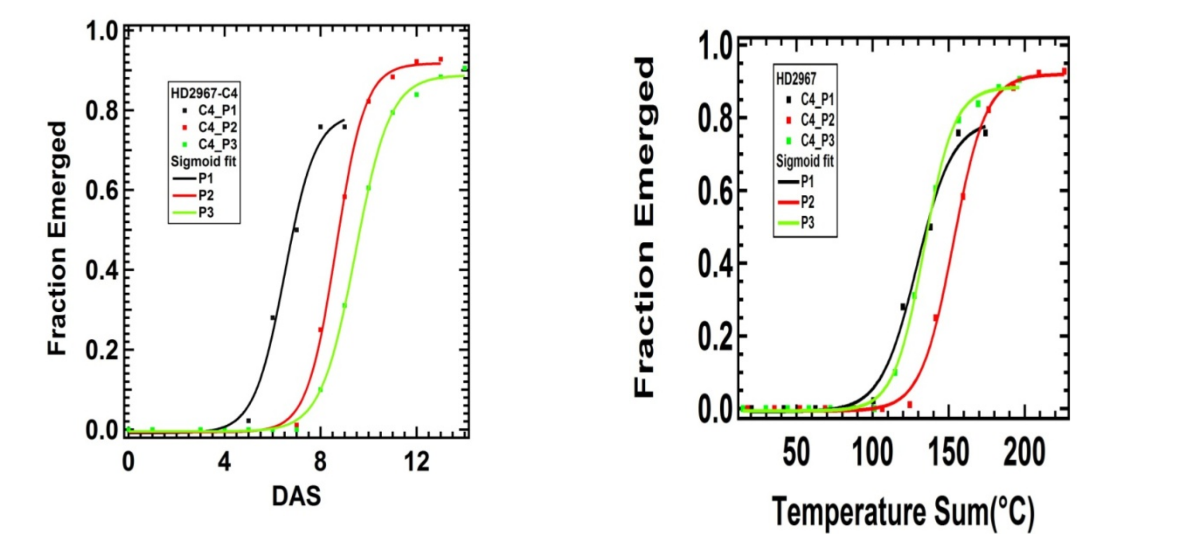


Figure 9: Emergence count as a function of Days after Sowing (**DAS**) and Thermal Sum for **HD2967(C4).**

HD2967 takes about 7 days to reach 50% of emergence for 1st sowing, around 9 days for both 2nd sowing and 3rd sowing. The temperature sum figure shows that there is increase in temperature sum reaching to 157°c for 2nd sowing and then temperature is getting low for 3rd sowing but is higher than 1st sowing.

WH1105 (C5):

Figure 10 shows us the emergence count fraction of **WH1105(C5)** for all the different sowing dates. The left hand side shows the emergence count as a function of Days after Sowing (DAS), and the right hand side about emergence count as a function of Thermal sum. The y-axis shows the fraction of 180 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

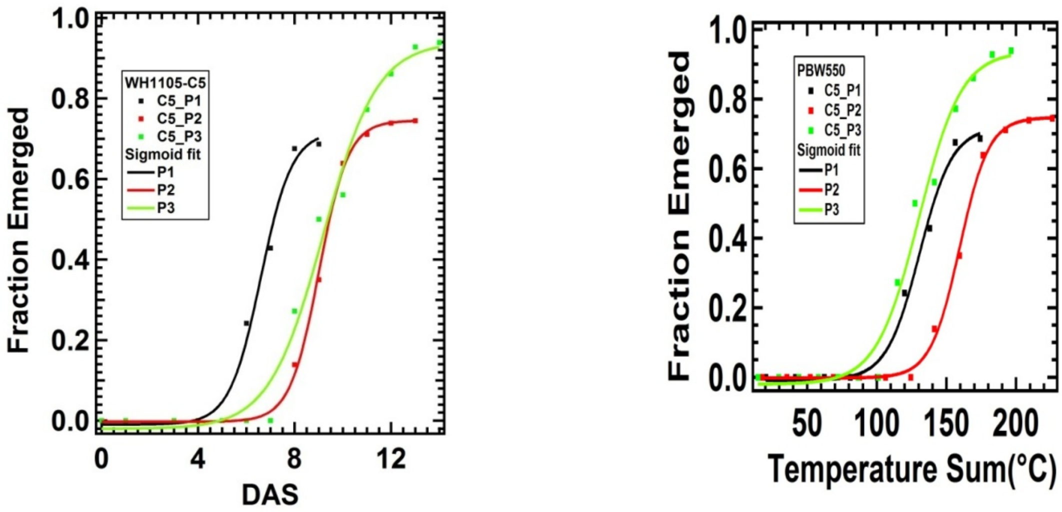


Figure 10: Emergence count as a function of Days after Sowing (**DAS**) and Thermal Sum for **WH1105(C5).**

WH1105 takes about 7 days to reach 50% of emergence for 1st sowing, and 9 days for both 2nd sowing and 3rd sowing. There is a high increase in temperature sum figure (159^{o}c) for 2nd sowing and then temperature is getting low for 3rd sowing but is almost equal to the1st sowing.

From above **figures(6,7,8,9,10)** we conclude that for all five different cultivars – when sowed early(1st sowing) the emergence growth takes equal amount of time. But for late sowing(2nd and 3rd sowing) the cultivars take more time to reach emergence growth. Also when observed from **Table 1** there is a gap for 15 days prior to 2nd and 3rd sowing, 2nd sowing (15/11/2018) induces drastic increase in thermal sum.

3.3.2 Flag leaf

Table 2 : Flag leaf data recorded for **PBW550(C1), HD2687(C2), RAJ3765(C3), HD2967(C4),** and **WH1105(C5).**

PBW550(C1) :

Figure 11 shows us the flag leaf emergence count fraction of **PBW550(C1)** for all the different sowing dates. The left hand side shows the flag leaf count as a function of Days after Sowing (DAS), and the right hand side about flag leaf count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum post 58,68, and 66 days of sowing. Different sowing dates for the growing season 2018/19 - 1st

November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

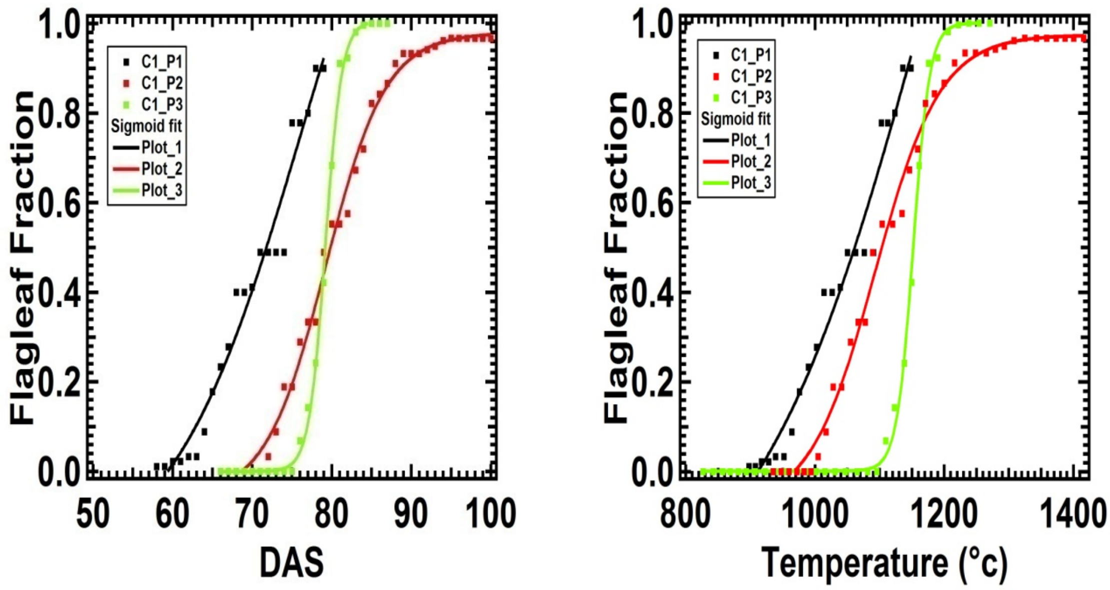


Figure 11: Flag leaf count as a function of Days after Sowing (**DAS**) and Thermal Sum for **PBW550(C1).**

For different sowing dates with a gap phase of 15 days the figure shows a difference in emergence of flag leaf stage and on the other hand an absolute difference in their temperature sum.

HD2687 (C2) :

Figure 12 shows us the flag leaf emergence count fraction of **HD2687 (C2)** for all the different sowing dates. The left hand side shows the flag leaf count as a function of Days after Sowing (DAS), and the right hand side about flag leaf count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum post 58,68, and 66 days of sowing. Different sowing dates for the growing season 2018/19 - 1st

November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

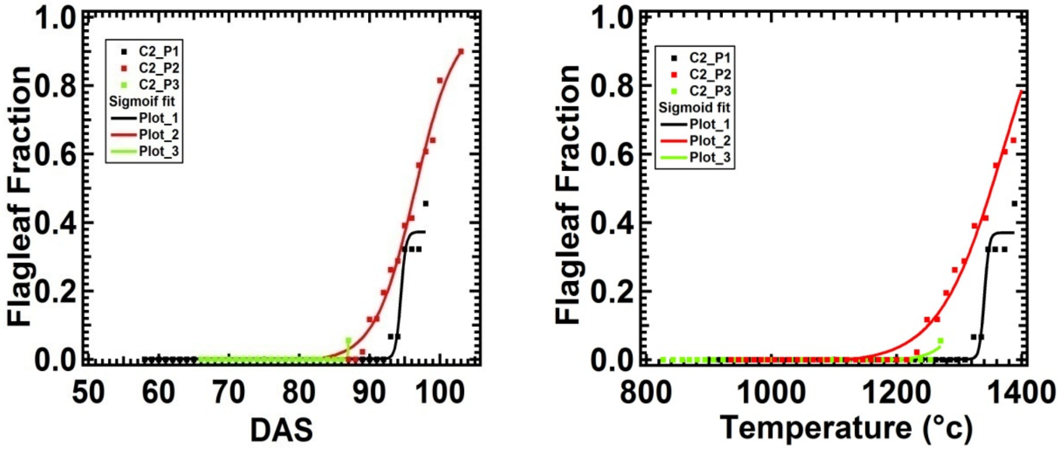


Figure 12: Flag leaf count as a function of Days after Sowing (**DAS**) and Thermal Sum for **HD2687 (C2).**

It can be seen from the graph that HD2687 (C2)reaches flag leaf in a shorter period of time despite of a lower thermal sum. While plot 3 grows slowly.

RAJ3765(C3) :

Figure 13 shows us the flag leaf emergence count fraction of **RAJ3765(C3)** for all the different sowing dates. The left hand side shows the flag leaf count as a function of Days after Sowing (DAS), and the right hand side about flag leaf count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum post 58,68, and 66 days of sowing. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

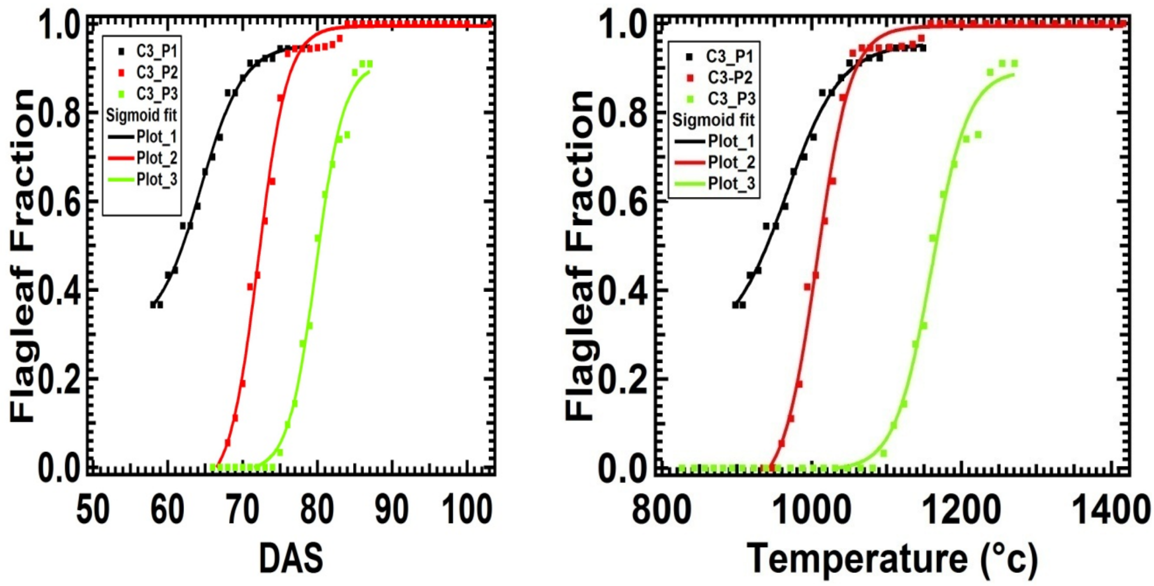


Figure 13 : Flag leaf count as a function of Days after Sowing (**DAS**) and Thermal Sum for **RAJ3765(C3).**

Irrespective of sowing time RAJ3765 reaches flag leaf emergence stage with almost same time. It is barely a difference of about 4-5 days for early and late sowing.

HD2967(C4) :

Figure 14 shows us the flag leaf emergence count fraction of **HD2967(C4)** for all the different sowing dates. The left hand side shows the flag leaf count as a function of Days after Sowing (DAS), and the right hand side about flag leaf count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum post 58,68, and 66 days of sowing. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.It can be seen from the graph that HD2967 cultivar on the other hand takes almost the same time and thermal time to the flag leaf stage irrespective of sowing time.

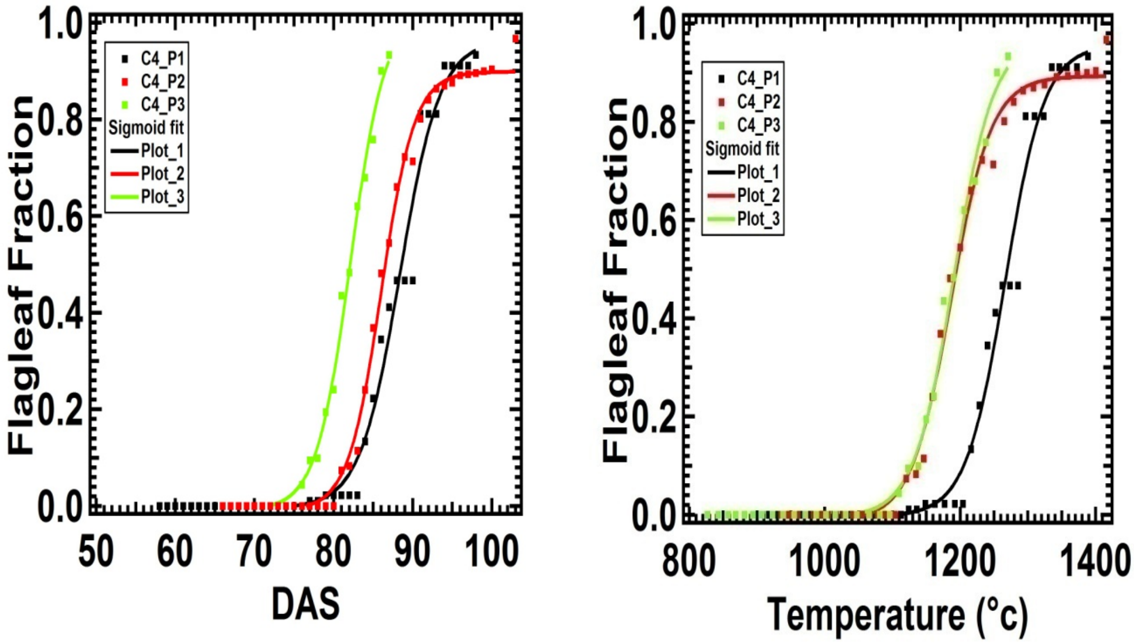


Figure 14 : Flag leaf count as a function of Days after Sowing (**DAS**) and Thermal Sum for **HD2967(C4).**

WH1105 (C5) :

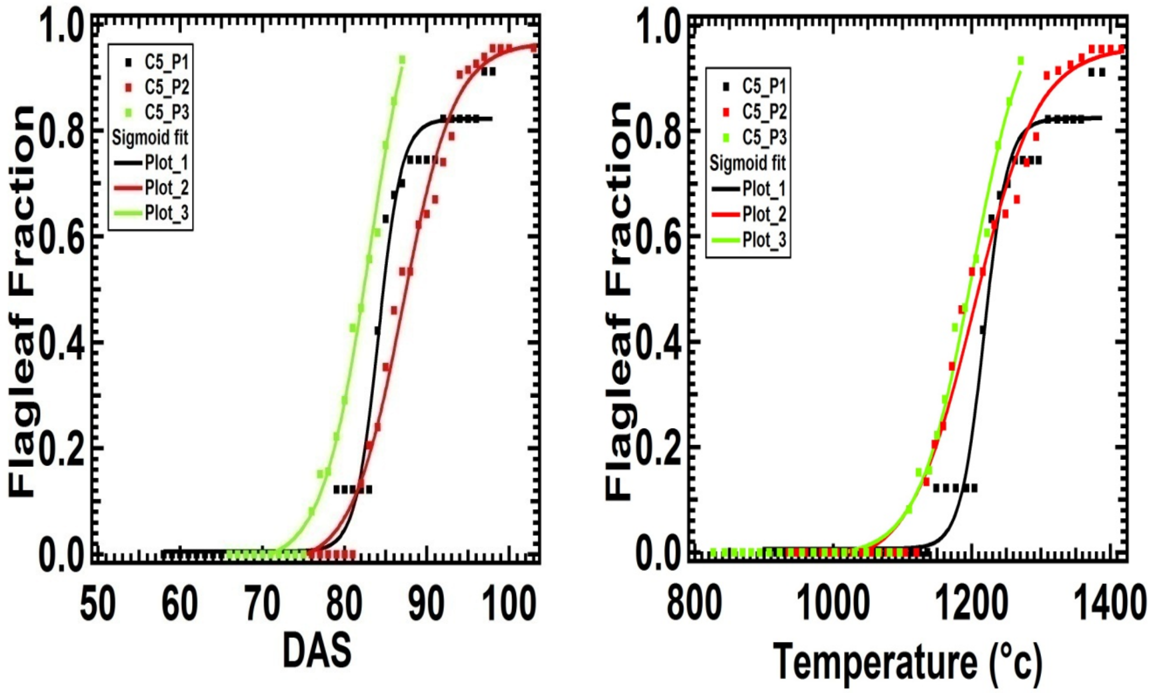


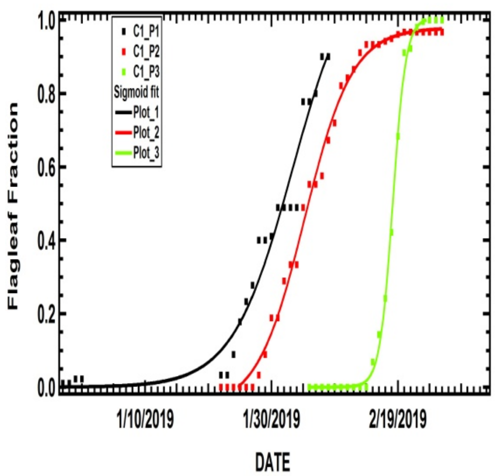
Figure 15: Flag leaf count as a function of Days after Sowing (**DAS**) and Thermal Sum for **WH1105 (C5).**

Figure 15 shows us the flag leaf emergence count fraction of **WH1105 (C5)** for all the different sowing dates. The left hand side shows the flag leaf count as a function of Days after Sowing (DAS), and the right hand side about flag leaf count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds that have emerged respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side, and for left hand side x-axis is marked for temperature sum post 58,68, and 66 days of sowing. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red, and 1st December with green colors respectively.

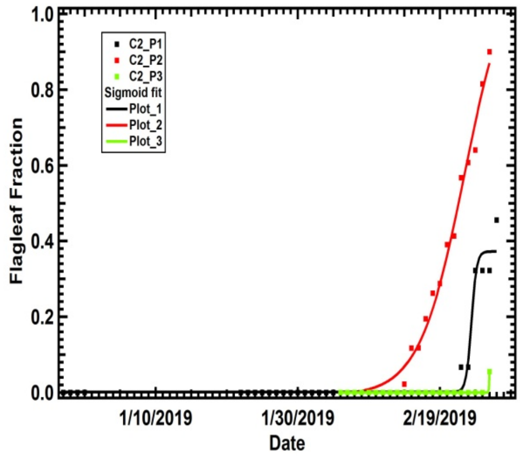
For WH1105 cultivar also there is not much difference in growing time and thermal time to reach flag leaf stage. It is barely a day faster for very late sowing.

Comparison of flag leaf emergence in all cultivars

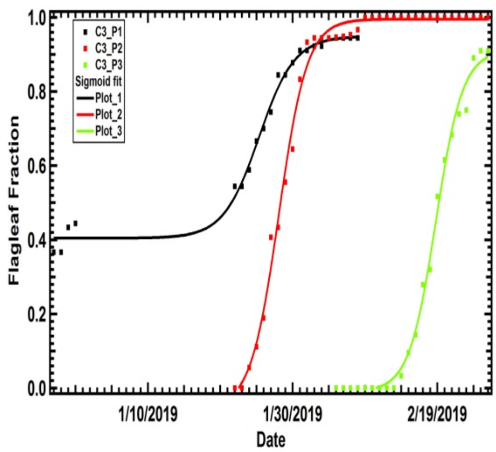
1 PBW550(C1)



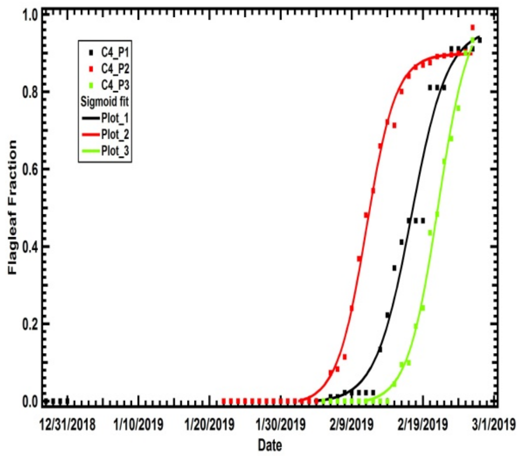
2 HD2687(C2)

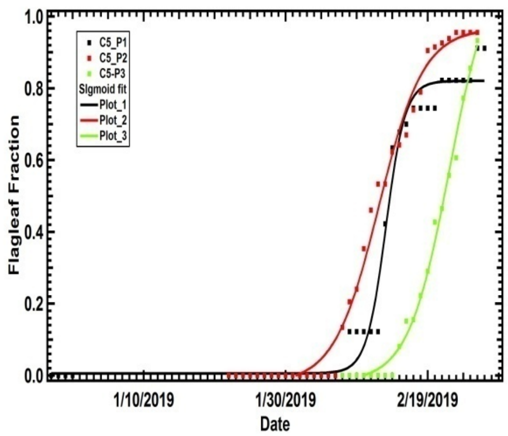


3 RAJ3765(C3)



4 HD2967(C4)





5. WH1105(C5)

Figure 16: Flag leaf fraction with Date This figure shows the flag leaf emergence fraction for all the five cultivars with three different sowing dates marked with

black(1st sowing), red(2nd sowing) and green(3rd sowing) colors respectively. The x-axis signifies date of flag leaf, and the Y-axis is the flag leaf fraction.

3.3.3 Heading

Table 3: heading data for all five cultivars for 2 different sowing dates (1st November and 15th November).

PBW550 (C1):

Figure 17 shows us the Head count fraction of **PBW550(C1)** for two different sowing dates. The left hand side shows the Head count as a function of Days after Sowing (DAS), and the right hand side about HEAD count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red color.

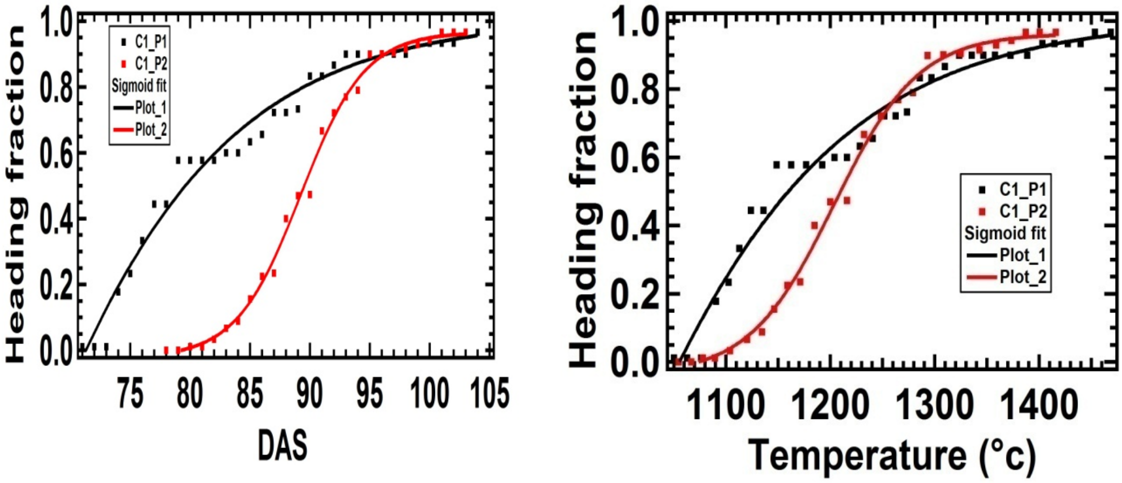


Figure 17: Heading count as a function of Days after Sowing (**DAS**) and Thermal Sum for **PBW550(C1).**

It can be seen from the graph that the cultivar shows head growth in a shorter time span and with a lower thermal time if sown early (1st November) as compared to when it is sown later (15th November).

HD2687 (C2):

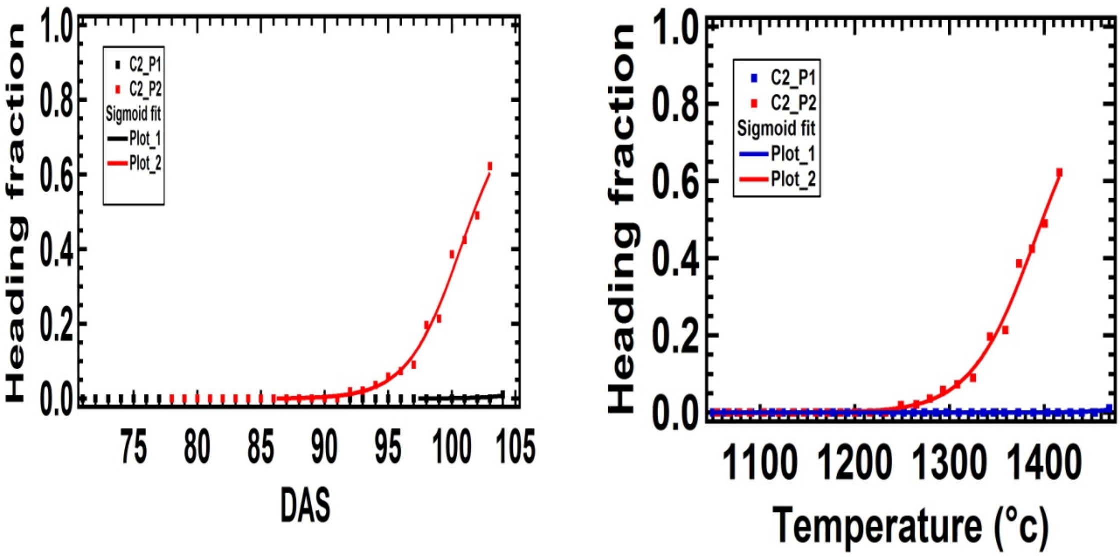


Figure 18: Heading count as a function of Days after Sowing (**DAS**) and Thermal Sum for **HD2687(C2).**

Figure 18 shows us the Head count fraction of **HD2687(C2)**for two different sowing dates. The left hand side shows the Head count as a function of Days after Sowing (DAS), and the right hand side about HEAD count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with blue, and 15thNovember is marked with red color.

It can be seen from the graph that the cultivar shows head growth in a longer time span and with a higher thermal time if sown early (1st November) as compared to when it is sown later (15th November).

RAJ3765 (C3):

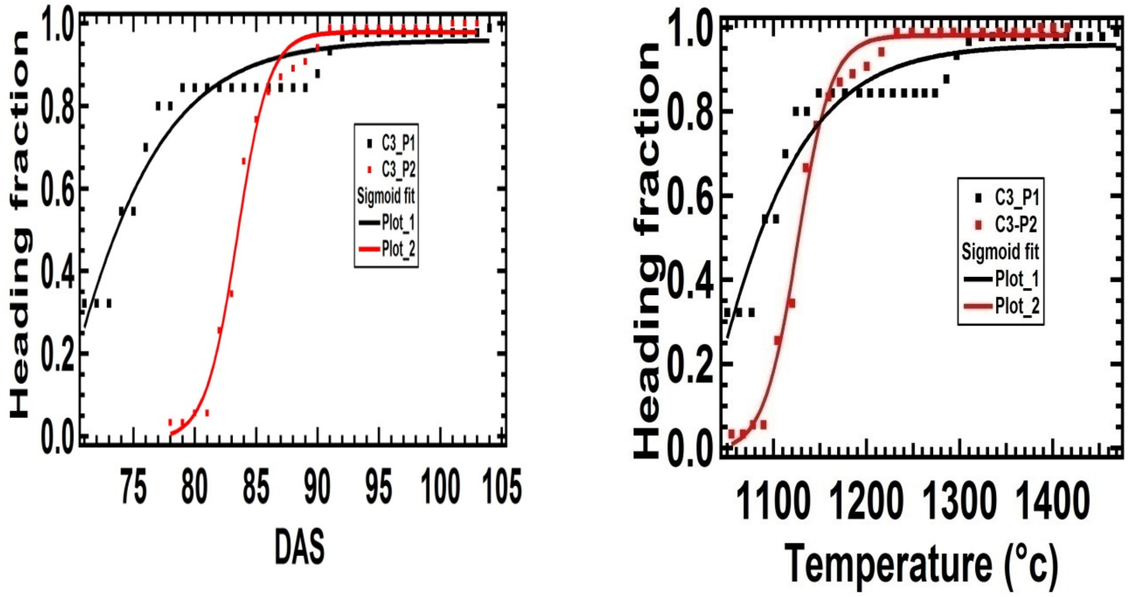


Figure 19 : Heading count as a function of Days after Sowing (**DAS**) and Thermal Sum for **RAJ3765 (C3).**

Figure 19 shows us the Head count fraction of **RAJ3765 (C3)**for two different sowing dates. The left hand side shows the Head count as a function of Days after Sowing (DAS), and the right hand side about HEAD count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red color.

It can be seen from the graph that the cultivar shows head growth in a shorter time span and with a lower thermal time if sown early (1st November) as compared to when it is sown later (15th November).

HD2967(C4) :

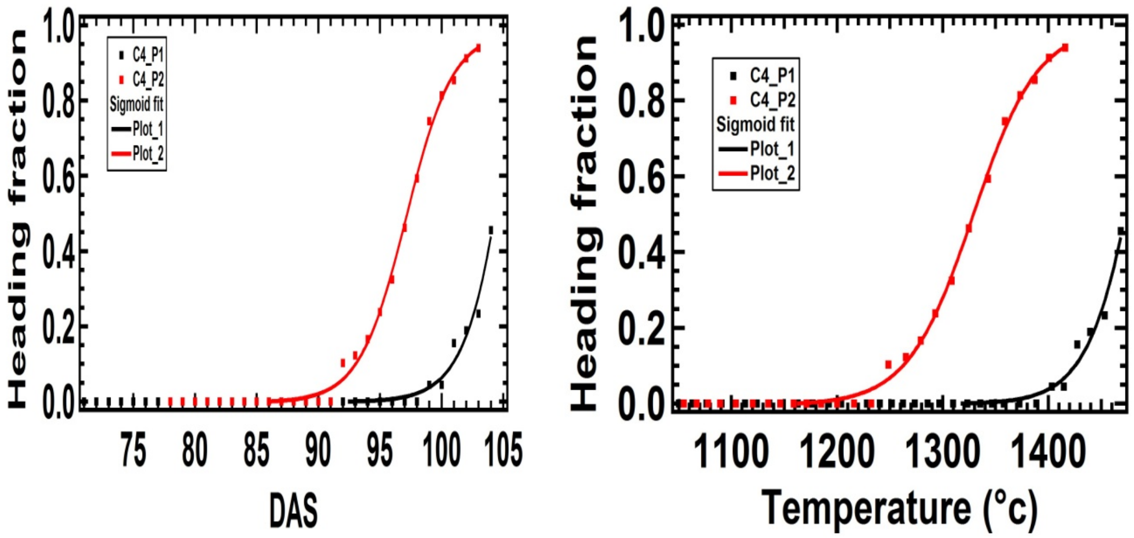


Figure 20 : Heading count as a function of Days after Sowing (**DAS**) and Thermal Sum for **HD2967(C4).**

Figure 20 shows us the Head count fraction of **HD2967(C4)** for two different sowing dates. The left hand side shows the Head count as a function of Days after Sowing (DAS), and the right hand side about HEAD count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red color.

It can be seen from the graph that the cultivar shows head growth in a longer time span and with a higher thermal time if sown early (1st November) as compared to when it is sown later (15th November).

WH1105 (C5):

Figure 21 shows us the Head count fraction of **WH1105(C5)** for two different sowing dates. The left hand side shows the Head count as a function of Days after Sowing (DAS), and the right hand side about HEAD count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 15th November is marked with red color.

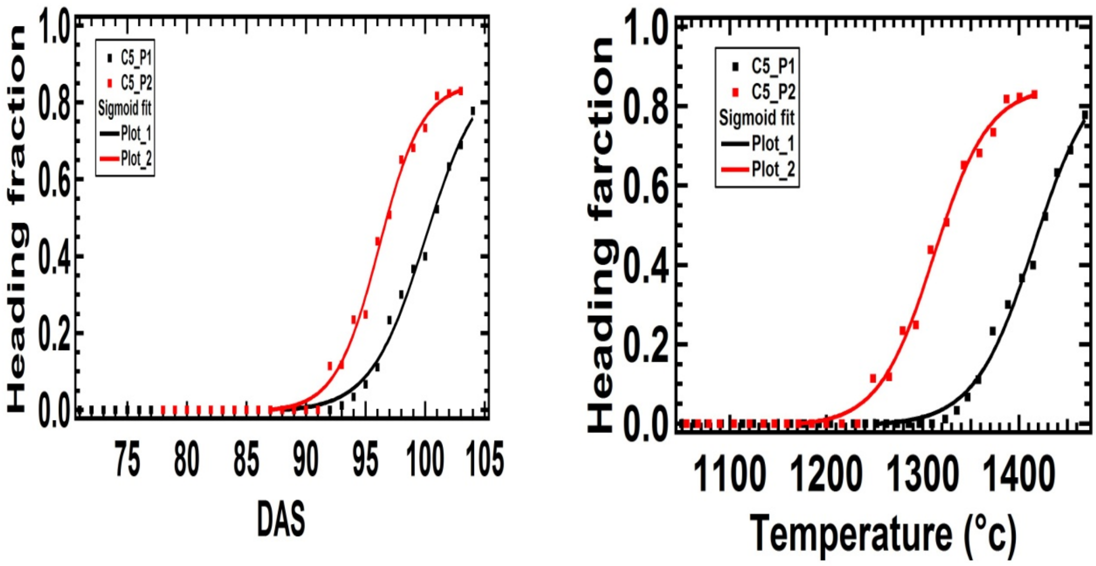


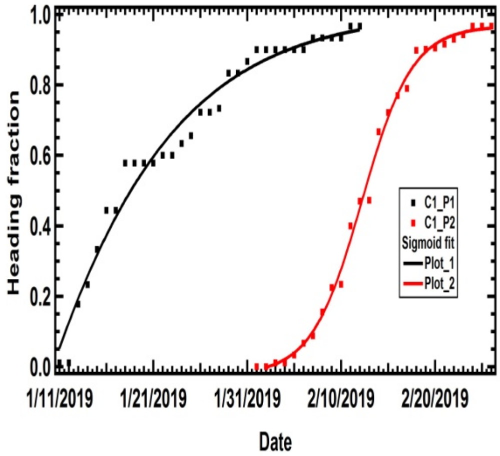
Figure 21: Heading count as a function of Days after Sowing (**DAS**) and Thermal Sum for **WH1105(C5).**

It can be seen from the graph that the cultivar shows head growth in a longer time span and with a higher thermal time if sown early (1st November) as compared to when it is sown later (15th November).

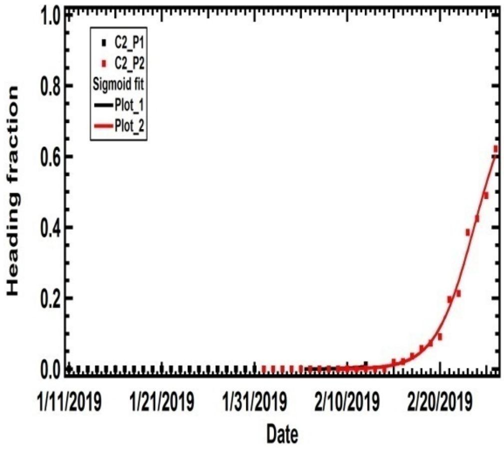
From the above graphs it can be observed that the cultivar shows head growth in a shorter time span and with a lower thermal time if sown late (15th November) as compared to when it is sown earlier (1st November). Because of earlier sowing the reproductive growth shifts to a time with lower temperatures and higher yields are expected for earlier sowing.

Comparison of heading in all cultivars

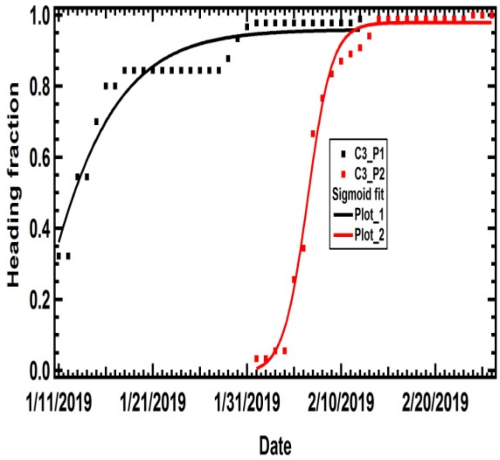
1. PBW550 (C1)



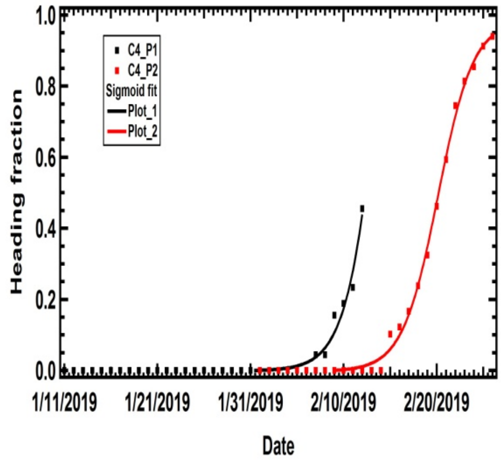
2. HD2687(C2)

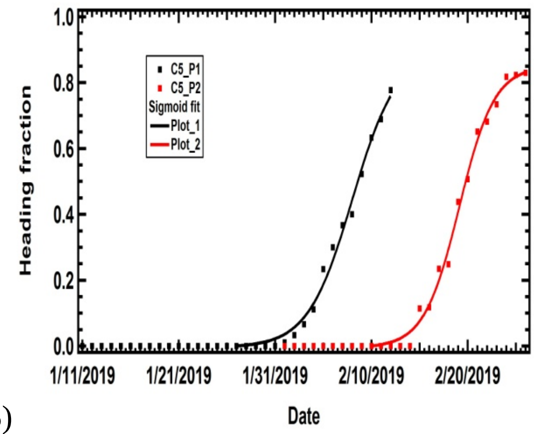


3. RAJ3765(C3)



4. HD2967(C4)





5.WH1105(C5)

Figure 22 :Heading fraction for cultivars with respect to Date

3.3.4: Anthesis

Table 4: Anthesis data for all five cultivars for 2 different sowing dates (1st November and 1ST December).

PBW550(C1):

Figure 23 shows us the Anthesis count fraction of **PBW550(C1)** for two different sowing dates. The left hand side shows the Anthesis count as a function of Days after Sowing (DAS), and the right hand side about Anthesis count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black, 1st December is marked with green color. From the data recorded and the graph, it was observed that anthesis for early sowing had a slight difference of days as compared to very late sowing.

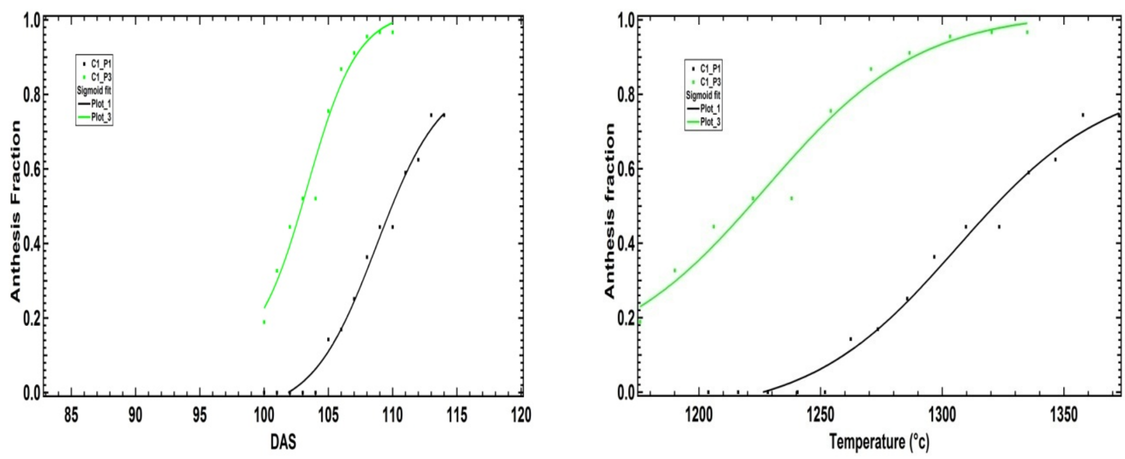


Figure 23: Anthesis count as a function of Days after Sowing (**DAS**) and Thermal Sum for **PBW550(C1).**

HD2687 (C2):

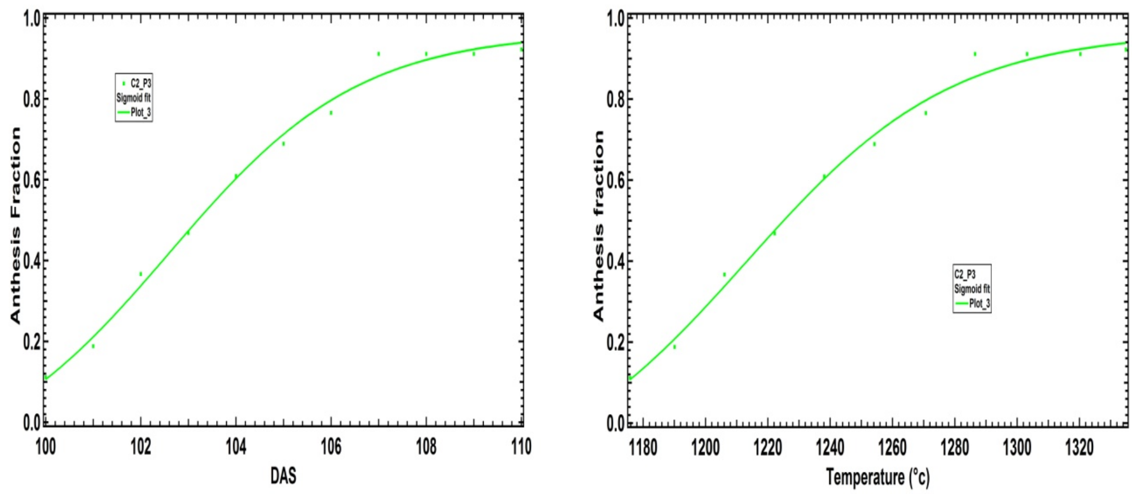


Figure 24: Anthesis count as a function of Days after Sowing (**DAS**) and Thermal Sum for**HD2687 (C2).**

Figure 24 shows us the Anthesis count fraction of **HD2687 (C2)**for two different sowing dates. The left hand side shows the Anthesis count as a function of Days after Sowing (DAS), and the right hand side about Anthesis count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st December is marked with green color. For very late sowing the cultivar took 103 days to reach anthesis. For at least 110 days HD2687 did show first fraction of anthesis for early sowing which was recorded.

RAJ3765 (C3):

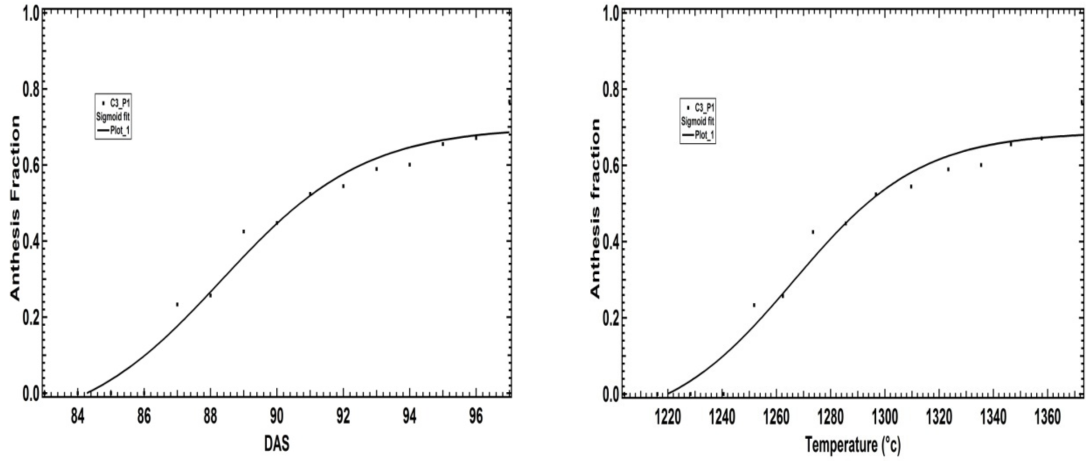


Figure 25: Anthesis count as a function of Days after Sowing (**DAS**) and Thermal Sum for**RAJ3765(C3).**

Figure 25 shows us the Anthesis count fraction of**RAJ3765(C3)** for two different sowing dates. The left hand side shows the Anthesis count as a function of Days after Sowing (DAS), and the right hand side about Anthesis count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st November is marked with black color. It took only 88 days to reach anthesis for RAJ3765 cultivar which has a quick rate for its growth.

HD2967(C4):

Figure 26 shows us the Anthesis count fraction of **HD2967(C4)**for two different sowing dates. The left hand side shows the Anthesis count as a function of Days after Sowing (DAS), and the right hand side about Anthesis count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st December is marked with green color.

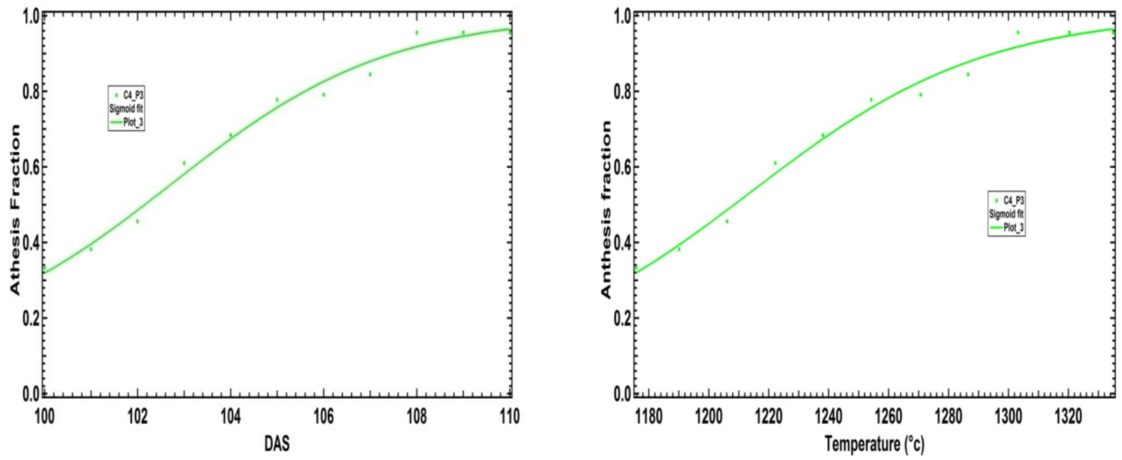


Figure 26: Anthesis count as a function of Days after Sowing (**DAS**) and Thermal Sum for**HD2967(C4).**

WH1105(C5) :

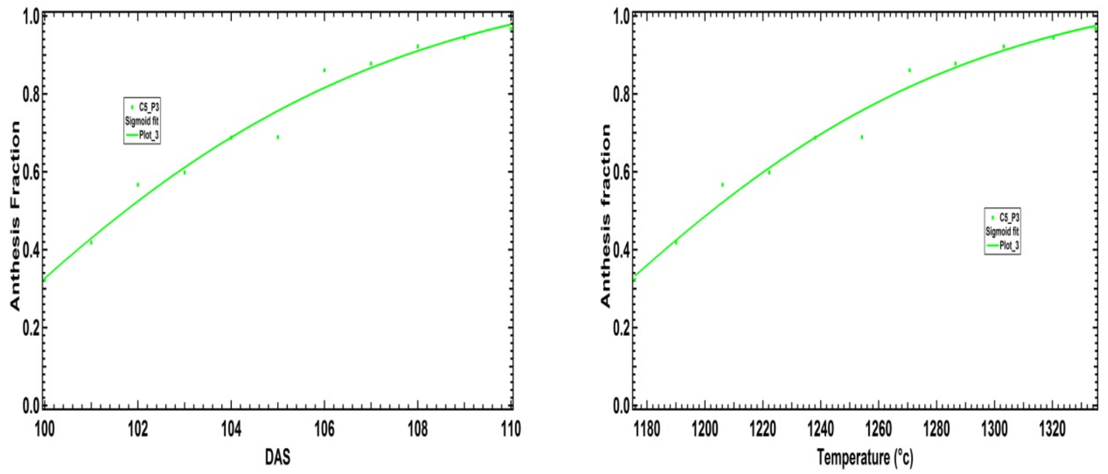
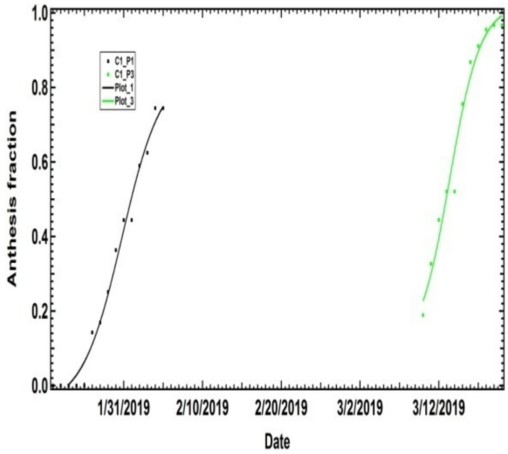


Figure 27: Anthesis count as a function of Days after Sowing (**DAS**) and Thermal Sum for**WH1105(C5).**

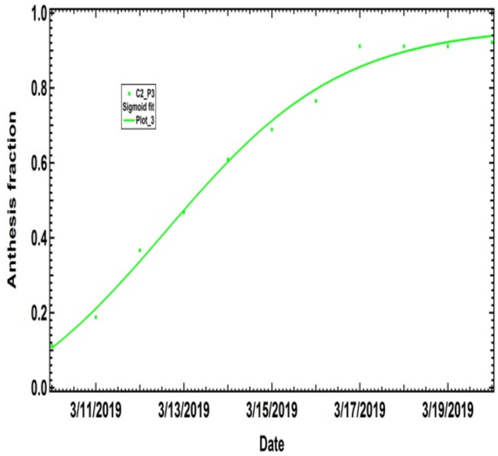
Figure 27 shows us the Anthesis count fraction of **WH1105(C5)**for two different sowing dates. The left hand side shows the Anthesis count as a function of Days after Sowing (DAS), and the right hand side about Anthesis count as a function of Thermal sum. The y-axis shows the fraction of 30 seeds respectively for both figures. The x-axis showing the numbers of days post sowing (DAS), for the right hand side and for left hand side x-axis is marked for temperature sum. Different sowing dates for the growing season 2018/19 - 1st December is marked with green color. The graph indicates that anthesis occurred within 103 days after sowing for late sowing.

Comparison of Anthesis date for all cultivars

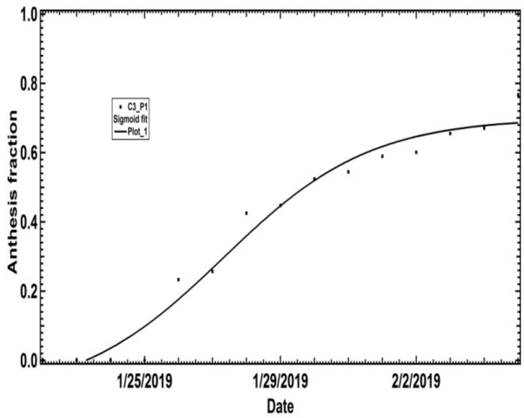
1 PBW550(C1)



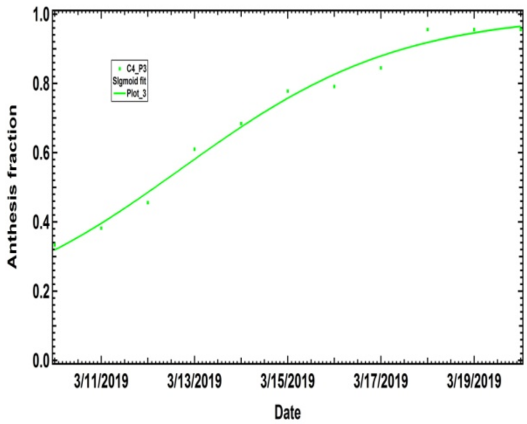
2 HD2687(C2)

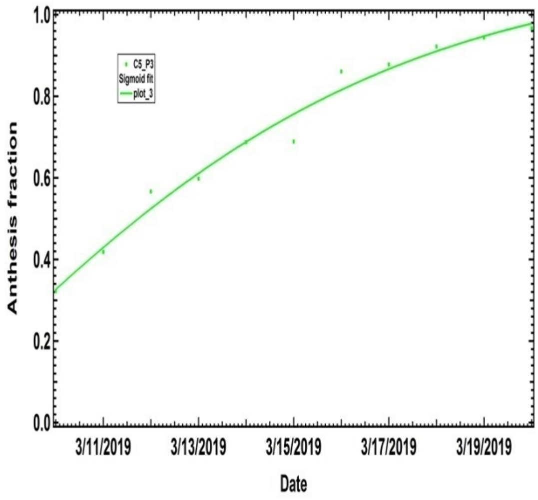


3 RAJ3765(C3)



4 HD2967(C4)





5 WH1105(C5)

Figure 28: Anthesis fraction for cultivars with respect to Date.

3.3.5: Yield attributes

Observations for head, active tillers, plant height of all the five cultivars during the three sowing dates(1st November, 15th November, 1st December) for growing season 2018-2019.

Table 5: Data recorded for all five cultivars **PBW550(C1), HD2687(C2), RAJ3765(C3), HD2967(C4), WH1105(C5)** showing average number of active tillers, average height of plant(cm) and average head length(cm).

The above data was measured manually using standard measuring scale. From the table it is known that or each cultivar the number of active tillers, plant height and head lengths decrease with later sowing. Early sowing can mitigate yield losses due to heat stress in all cultivars studied. HD2967(C4), WH1105(C5) shows increase in plant height for 2nd sowing.

Chapter 4

Conclusions

When sowing is done earlier (1/11/2018) in the growing season all five cultivars require low thermal sum to reach emergence. This is because during earlier days of winter day time temp is high.

There is not much difference in thermal sum to reach emergence for all five different cultivars for sowing dates15th Nov and 1st Dec)

Flagleaf emergence requires higher temp because higher temp are conducive for vegetative growth as the temp tends to drop reproductive growth is triggered. RAJ3765 requires least thermal sum among the five cultivars to reach the flagleaf stage.

RAJ 3765(C3) requires highest thermal sum to reach the Anthesis stage, and PBW550(C1), WH1105(C5) require low thermal sum. RAJ3765 (C3) requires highest thermal sum to reach anthesis because this cultivar is a hybrid form of wheat and can be grown in extremely hot conditions due to its heat tolerant traits.

When sowing is done late in the growing season cultivars are more prone to the heat stress during the flowering and grain filling stages. This adversely affects the crop yield and quality of the grains. It is also noticed that with late (1st December 2018) sowing the plant height reduces by a margin, also there is a decrease in average head length and average active number of tillers which will duly affect the crop yield leading to poor and unhealthy quality of grains. Therefore to prevent such measures early sowing can be considered a good time for gaining healthy quality of grains and maximum crop yield.

Bibliography

- Gaudel, A., Cooper, O.R., Ancellet, G., Barret, B., Boynard, A., Burrows, J.P., Clerbaux, C., Coheur, P.-F., Cuesta, J., Cuevas, E., Doniki, S., Dufour, G., Ebojie, F., Foret, G., Garcia, O., Granados Muños, M.J., Hannigan, J.W., Hase, F., Huang, G., Hassler, B., Hurtmans, D., Jaffe, D., Jones, N., Kalabokas, P., Kerridge, B., Kulawik, S.S., Latter, B., Leblanc, T., Le Flochmoën, E., Lin, W., Liu, J., Liu, X., Mahieu, E., McClure-Begley, A., Neu, J.L., Osman, M., Palm, M., Petetin, H., Petropavlovskikh, I., Querel, R., Rahpoe, N., Rozanov, A., Schultz, M.G., Schwab, J., Siddans, R., Smale, D., Steinbacher, M., Tanimoto, H., Tarasick, D.W., Thouret, V., Thompson, A.M., Trickl, T., Weatherhead, E., Wespes, C., Worden, H.M., Vigouroux, C., Xu, X., Zeng, G. and Ziemke, J., 2018. Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation. *Elem Sci Anth*, 6(1), p.39. DOI:http://doi.org/10.1525/elementa.291
- Sinha, B., Singh Sangwan, K., Maurya, Y., Kumar, V., Sarkar, C., Chandra, B. P., and Sinha, V.: Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements, Atmos. Chem. Phys., 15, 9555-9576, https://doi.org/10.5194/acp-15-9555-2015, 2015.
- B.J. Finlayson-Pitts & J.N. Pitts Jr. (1993) Atmospheric Chemistry of Tropospheric Ozone Formation: Scientific and Regulatory Implications, Air & Waste, 43:8,1091-1100, DOI: 10.1080/1073161X.1993.10467187.
- E. Ainsworth, C. R. Yendrek, S. Sitch, W. J. Collins, and L. D. Emberson, "The effects of tropospheric ozone on net primary productivity and implications for climate change.," *Annu. Rev. Plant Biol.*, vol. 63, no. March, pp. 637–61, 2012
- Pleijel, H., Skärby, L., Wallin, G., and Sellden, G.: Yield and grainquality of spring wheat (triticum aestivum l., cv. drabant) exposed to different concentrations of ozone in open–top chambers, Agr. Environ. Pollut., 69, 151–168, 1991.
- E. Ainsworth, C. R. Yendrek, S. Sitch, W. J. Collins, and L. D. Emberson, "The effects of tropospheric ozone on net primary productivity and implications for climate change.," *Annu. Rev. Plant Biol.*, vol. 63, no. March, pp. 637–61, 2012.

- Sarkar, C., Kumar, V., & Sinha, V. (2013). Massive emissions of carcinogenic benzenoids from paddy residue burning in North India. *Current Science*, *104*(12), 1703–1709.
- Sinha, V., Kumar, V., & Sarkar, C. (2014). Chemical composition of pre-monsoon air in the Indo-Gangetic Plain measured using a new air quality facility and PTR-MS: High surface ozone and strong influence of biomass burning. *Atmospheric Chemistry and Physics*, *14*(12), 5921–5941. https://doi.org/10.5194/acp-14-5921-2014.
- Sutinen, S. (1987). Ultrastructure of mesophyll cells of spruce needles exposed to O3 alone and together with SO2. *European Journal of Forest Pathology*, *17*(6), 362–368. https://doi.org/10.1111/j.1439-0329.1987.tb01329.x.
- Feng, Z., Wang, L., Pleijel, H., Zhu, J., & Kobayashi, K. (2016). Differential effects of ozone on photosynthesis of winter wheat among cultivars depend on antioxidative enzymes rather than stomatal conductance. *Science of the Total Environment*, *572*, 404–411. https://doi.org/10.1016/j.scitotenv.2016.08.083.
- P. R. Shewry, Wheat, *Journal of Experimental Botany*, Volume 60, Issue 6, April 2009, Pages 1537–1553, https://doi.org/10.1093/jxb/erp058