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Heat units associated with maize (*Zea mays* L.) development

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Abstract

Temperature is a measure of the amount of heat that affects the growth and development of maize. The concept of heat units is widely used in phenological studies, particularly for predicting phenological changes in living organisms. A direct method for calculating heat units is through the estimation of growing degree days (GDD), which quantifies the relationship between maize phenology and temperature. A literature review was conducted on the effects of temperature, especially GDD, to evaluate phenological changes and their relationship with agronomic management practices in maize cultivation. This study was carried out in 2024 and drew upon recent information from the scientific databases Science Direct and Redalyc, consulting research articles focused on agroclimatic indices applied to maize cultivation. The paper presents a theoretical framework integrating various case studies and synthesizing information generated in major maize-producing regions worldwide, resulting in a broad set of interrelated concepts that enhance understanding of the topic. Based on this review, it has been documented that GDD represents a simple and widely used method for monitoring and estimating phenological stages in maize; however, their application depends on adequate agronomic and environmental knowledge.

Keywords: air temperature, heat units, thermal time, maize phenology.

Introduction

Agronomic zoning studies contribute to the adaptation of agricultural systems and to the identification of the specific characteristics of a region. They provide information for the planning of agricultural activities and incorporate climatic and agronomic indicators that are useful for identifying potential areas for the establishment of productive systems. Furthermore, these studies contribute to the development of mitigation and adaptation strategies in response to climate change (Mathieu & Aires, 2018). Agrochemical indices are defined based on the relationships among crops, yield, management practices, and climate variability. They are used to assess the optimal climatic conditions required to achieve the desired agricultural productivity (Satapathy et al., 2021).

Climate is a limiting factor that directly influences agriculture practices; therefore, it must be considered in agricultural planning (Cruz-González et al., 2024). Temperature is a key factor controlling plant development rates and crop

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yield. However, extreme temperatures can act as limiting factors by slowing plant growth, causing physiological injury, or even leading to plant mortality (Mishra et al., 2023). Deviations in temperature above or below specific thresholds during the growing season trigger cold and heat s tress in various agricultural crops, thereby restricting growth and metabolic processes and resulting in crop losses worldwide (Kim & Lee, 2023).

A set of agroclimatic indices based on air temperature has been established for use in various agricultural practices. By means of a single numerical value, these indices facilitate the assessment of differences in crop growth conditions, as well as the characterization of crop species adaptations and their respective regions of suitability (Lysiak & Szot, 2023; Lu et al., 2021). Some of the indices reported in the literature include biological temperature, the cool night index, the apparent temperature, mean growing season temperature, effective accumulated temperature, the sum of effective temperatures, and growing degree days, among others (Mathieu & Aires, 2018).

The Growing Degree Days (GDD) index is based on the linear relationship between the time required to reach a given phenological stage and temperature within the range defined by the mean temperature and a base temperature (Jan et al., 2022). The GDD index is widely used to determine the length of plant phenological stages and to assess the extent of the growing season across different locations. It also enables the prediction of planting dates, harvest onset, and crop cycle duration (Ortez et al., 2023; Elnesr & Alazba, 2016).

In maize, the progression between phenological stages and the final leaf number per plant can differ substantially among varieties. Early-maturing varieties produce fewer leaves or progress through their growth stages more rapidly compared to late-maturing varieties, which tend to develop at a slower pace. This significant variation in development time may be attributed to differences in geographic locations, genetic factors, planting dates, crop management practices, seasonal conditions, and environmental stress (Khalilzadeh & Wang, 2022).

Maize accounted for more than 30 % of global cereal production in 2023, with a cultivated area exceeding 1.6 billion hectares. It is considered the most important crop in terms of production volume and human consumption after wheat (FAO, 2024). The objective of this study was to conduct a literature review on the effect of temperature, particularly Growing Degree Days (GDD), to evaluate phenological changes in maize growth and development.

Air temperature and its effects on crops

In agriculture, crop yield depends on different factors such as genetics, soil properties, irrigation, crop management, fertilization, among others; however, climate is a not-controllable environmental factor that plays an important role in crop development and ultimately determines its success and profitability (Mathieu & Aires, 2018). Precipitation and temperature are the climatic variables that most affect crop performance. Temperature plays a critical role in agriculture systems because fluctuations in this parameter alter the thermal energy accessible to plants, thereby influencing crop production and quality (Lu et al., 2021; Elnesr & Alazba, 2016).

Temperature regulates fundamental physiological processes in plants, including photosynthesis, transpiration, and respiration (Mishra et al., 2023). Air temperature is also closely associated with other environmental variables, such as photoperiod, solar radiation, and soil temperature (Lysiak & Szot, 2023). Crop physiology during the growing season is driven more by the accumulation of heat units than by instantaneous air temperature (Kukal & Irmak, 2018). Heat accumulation is used to predict crop growth and development, yield potential, water uptake, nutrient absorption, and stress conditions (Mishra et al., 2023).

Heat accumulation in crops

In plants, growth and development can be characterized by the number of days between phenological stages (Ortez et al., 2023). An example is the time required for a species to progress from flowering to fruit maturity. These stages are influenced by temperature; however, temperature alone is not a direct measure of their progression. To achieve a more accurate assessment, developmental events can be expressed in terms of developmental units, or physiological time, rather than chronological time. For this purpose, heat units (HU) are commonly used (Klepper, 2023).

Heat units (HU) are used to quantify the accumulation of heat, or temperature units over time, and serve as measures of the time a crop experiences temperatures suitable for its development. They are also employed to estimate the growth stage of plants (Khalilzadeh & Wang, 2022; Gilmore & Rogers, 1958). The use of HU increases the precision in determining the duration of the developmental cycle, but accurate results are only achieved when HU are calculated using values close to the threshold temperatures (maximum and minimum) that regulate the development of the species (Łysiak & Szot, 2023; Mangani et al., 2023).

Cardinal temperatures of maize

Air temperature is the most important climatic parameter, because it influences the physical and chemical process within maize plants, which in turn control biological reactions (Waqas et al., 2021). Each maize accession has its own maximum, optimum, and minimum temperature limits for normal growth and reproduction. These three thresholds are referred to as the cardinal temperatures (Beegum et al., 2023; Rai et al., 2014).

As temperature decreases, the development rate of maize slows, and if the temperature drops sufficiently, development ceases at the lower developmental threshold of the organism, often referred to as the base temperature (Tbase). As temperature increases, the development rate rises until it reaches the optimum temperature (Topt), above which the development rate of maize declines and eventually stops at a value known as the maximum temperature (Tmax) (Walne & Kambham, 2022).

Sánchez et al. (2014) compiled data from 140 scientific articles covering different maize-producing regions worldwide to determine the key temperature thresholds and the crop's response to extreme temperature effects. Table 1 shows the averages obtained for lethal temperatures and cardinal temperatures across the different phenological stages and developmental phases of maize.

Growing Degree Days

Growing Degree Days (GDD), or thermal time, is an important indicator for understanding the phenology of a crop (Sharma et al., 2021). The GDD index is widely used to study changes in growth conditions over time and across space, incorporating air temperature into the thermal potential of a region with crop-specific temperature thresholds (Kukal & Irmak, 2018). Growing Degree Days are commonly used as a measure of the amount of heat required for a crop to reach a particular phenological stage. It is defined as the number of degrees by which the daily temperature exceeds a base temperature (Mangani et al., 2023; Sharma et al., 2021).

Growing Degree Days are a tool used in the agricultural sector to predict seedling emergence (Beegum et al., 2023); to classify different maize accessions from earlier to later maturity, considering different base temperatures (Arista-Cortes et al., 2018); and to identify periods of water deficit during different phenological stages (Prasad et al., 2018). GDD are also used to determine the nutritional value of a crop according to its development duration (Barrientos-Blanco et al., 2024); to establish the optimal date for seedling transplanting (Jan et al., 2022); to calculate and assess effects across different growth stages (Anandhi, 2016); and to identify dry years or years with extreme heat (Jiang et al., 2021). In agronomic zoning studies, GDD are used to geographically define areas with the highest suitability (Neamatollahi et al., 2012); to estimate potential future

Table 1. Summary of temperatures for different phenological stages of maize.

Stages		°C
Lethal limits	Tbase	-1.8
	Tmax	46
Leaf initiation	Tbase	7.3
	Topt	31.1
	Tmax	41.3
Shoot growth	Tbase	10.9
	Topt	31.1
	Tmax	38.9
Root growth	Tbase	12.6
	Topt	26.3
	Tmax	40.1
Planting to emergence	Tbase	10
	Topt	29.3
	Tmax	40.2
Planting to tassel initiation	Tbase	9.3
	Topt	28.3
	Tmax	39.2
Flowering	Tbase	7.7
	Topt	30.5
	Tmax	37.3
Grain filling	Tbase	8
	Topt	26.4
	Tmax	36
Whole plant	Tbase	6.2
	Topt	30.8
	Tmax	42

yield under climate change projections (Žydelis et al., 2021); and to serve as a planting calendar tool to minimize the risk of frost and extreme temperatures (Prasad et al., 2018), among other applications.

Estimation of GDD

Growing Degree Days (GDD) have been used since they were first proposed by Gilmore & Rogers (1958) to monitor crop development. GDD are calculated daily by averaging the minimum and maximum daily temperatures and subtracting a base temperature, as follows:

$$GDD = \frac{(T_{max} + T_{min})}{2} - T_{base}$$

Where: Tmax and Tmin represent the daily maximum and minimum air temperatures (°C), while

Tbase represents the base temperature (°C) below which growth does not occur.

The GDD concept assumes the existence of a base or threshold temperature at which plants growth stops or is minimal (Sharma et al., 2021). A base temperature of 10 °C is assumed for warm-season crops such as maize, sorghum, and millet, whereas a lower base temperature of 5 °C to 0 °C is commonly assumed for cool-season crops such as wheat, oats, and barley (Anandhi, 2016). The rate of plant growth increases as the temperature rises above the base or threshold temperature. The duration of the crop growing season is closely linked to the accumulation of GDD from sowing to maturity (Ren et al., 2022).

GDD in maize production

The growth cycle of maize consists of three main phases: vegetative, reproductive, and maturation, although each phase includes more specific developmental stages. At each penological stage, maize requires different accumulation of GDD to reach the subsequent stage (Table 2) (Beegum et al., 2023; Sifuentes-Ibarra et al., 2020).

Maize crop phenology

Phenology defines the physiological development stages of crops, from planting to harvest (Jan et al., 2022). Effective crop growth management and yield estimation required precise information on crop phenology throughout the growing season (Gao & Zhang, 2021). Plant phenology is quantitively analyzed using accumulated heat units, since the plant's energy requirements fall within a specific range. The calculation of heat units in a seasonal crop is estimated for the periods of growth, development, and harvest (Łysiak & Szot, 2023). The thermal energy required to reach a specific plant growth or developmental stage can be calculated by recording the ambient temperature experienced by the plant (Walne & Kambham, 2022). Phenology examines the relationship between plant developmental stages and environmental factors (Klepper, 2023). It serves as an ecological indicator for understanding plant responses to climatic variation (Łysiak & Szot, 2023), and its study is essential for improving plant growth and development, as well as facilitating effective agricultural management. A phenological stage refers to a single point in maize development, such as flowering, whereas a phe-

Table 2. Growing Degree Day (GGD) requirements for maize at different growth stages.

Comer et al., 2017		Leguizamón, et al., 2012		Neamatollahi et al., 2012		Qian et al., 2019		Lozano, 2021		Ojeda et al., 2006	
Ontario, Canada		Córdoba, Argentina		Jorasán, Iran		Iowa, USA		Veracruz, Mexico		Sinaloa, Mexico	
Stage	GDD	Stage	GDD	Stage	GDD	Stage	GDD	Stage	GDD	Stage	GDD
VE	180	V4	520	V2	200	V2	123	VE	63	VE	109
V1	330	V8	778	V6	475	V4	417	VT	811	V4	316
V4	630	V13	963	V12	870	V8	744	R1	873	V8	502
V6	680	VT	1067	VT	1135	V10	916	R2	1000	V10	576
V8	930	R5	1289	R1	1400	V14	1279	R3	1094	VT	665
V12	1270			R5	2450	VT	1673	R4	1194	R1	823
VT	1310			R6	2700	R1	1888	R5	1302	R3	1102
R1	1480					R5	2500	R6	1633	R6	1451
R2	1825					R6	2899				
R3	2000										
R4	2165										
R5	2475										
R6	2800										

VE-Emergence, V1-First leaf fully developed, V4-Second leaf fully developed, V6- Sixth leaf fully developed, V8-Eight leaf fully developed, V12- Twelfth leaf fully developed, VT Tasseling/Flowering, R1-Silking (stigma emergence), R2-Blister stage, R3-Milk stage, R4-Dough stage, R5-Dent stage and R6-Physiological maturity.

nological phase represents the time interval between two stages, for example, from grain filling to maturity (Alsubhi & Alzahrani, 2023; Ren et al., 2022).

Crop phenology (growth stage) varies by year and geographic location and is influenced by climatic variability, local weather, soil properties, and anthropogenic activities. The crop growth stage begins at planting or emergence and ends at harvest. Crop planting dates depend on soil temperature and moisture, climatic conditions, and farmer's management practices (Gao & Zhang, 2021).

Environmental factors, such as temperature, precipitation, and solar radiation, directly or indirectly regulate the timing of phenological events or can as triggers that set a plant's internal biological clock. Moreover, phenological changes induced by environmental factors vary according to the response and sensitivity of different plant organs, including leaves, flowers, fruits, and the root system (Alsubhi & Alzahrani, 2023; Guo et al., 2020).

Maize growth and development can be divided into distinct vegetative (V) and reproductive (R) stages, and the rates at which the plant reaches various developmental stages can be quantified using accumulated crop heat units. Based on temperature, the maize growth stages (from emergence to physiological maturity) are shown in Table 3 and illustrated in Figure (Vega-Serratos et al., 2018; Linker & Kisekka, 2017).

Table 3. Phenological stages of maize development and the GDD required to reach each stage.

Stage	Description	GDD	Phenological stage
VE	Emergence	120	Planting and germination
V1	First fully expanded leaf	75-85	Vegetative development
V4	Second fully expanded leaf	75-85	
V6	Sixth fully expanded leaf	75-85	
V8	Eight fully expanded leaf	75-85	
V12	Twelfth fully expanded leaf	75-85	
VT	Tasseling/flowering	55-65	Flowering
R1	Silking (Stigma emergence)	60-65	
R2	Blister stage	70-75	Grain filling and maturation
R3	Milk stage	80-85	
R4	Dough stage	90-95	
R5	Dent stage	100-105	
R6	Physiological maturity	110-130	

Source: Ransom and Endres, 2020, Comer et al., 2017.

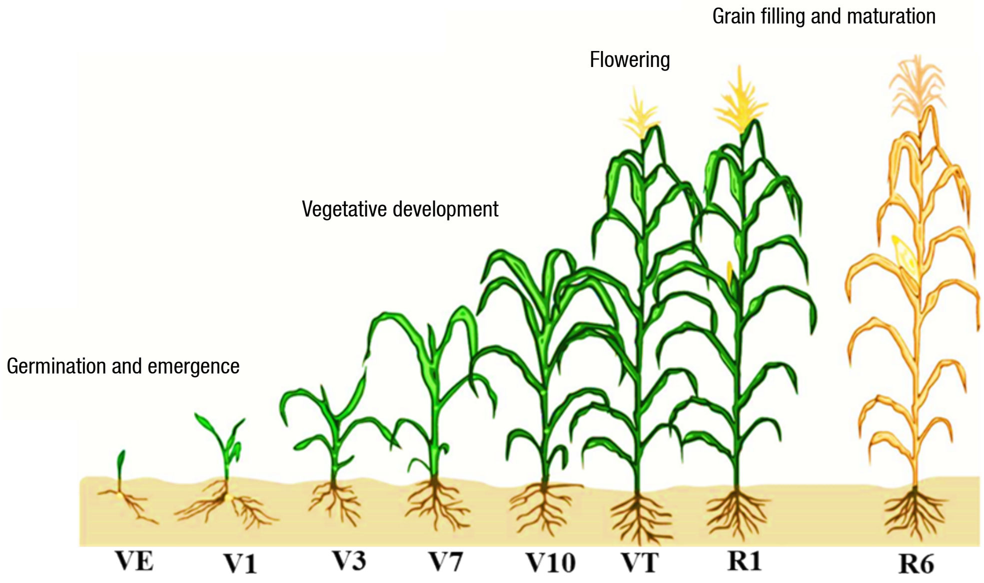

Figure 1. Maize growth stages from emergence to maturity

Source: Figure adapted from Alam et al., 2021.

Alam et al. (2021) and Linker & Kisekka (2017) identified that the emergence stage (VE) begins about 4 to 5 days after planting under ideal conditions but may take up to 2 weeks or more under cool or dry conditions. During stage V1–V5, 1 to 5 leaves appear; at this stage, the potential number of leaves and ears is determined. Stages V6–V8 occur within 4 to 6 weeks after VE. Stages V9-V11 occur between 6 to 8 weeks after VE. By V12, the plant is nearly 121 cm tall or taller. Flowering (VT) begins approximately 9 to 10 weeks after emergence. At stage R1, maize plants enter reproductive growth after completing tassel emergence, although reproductive stages are defined by kernel development. Stage R6 corresponds to physiological maturity, at this point, the kernel has reached its maximum dry weight, which occurs about 60 days the flowering stage.

GDD reported in Mexico

In the municipality of Celaya, Guanajuato, Noriega et al. (2011) identified that 757 accumulated GDD are required in four hybrid maize genotypes from crop emergence to physiological maturity. Arista-Cortes et al. (2018) determined the GDD needed to reach the female flowering stage for different landrace maize accessions in the states of Chiapas, Hidalgo, San Luis Potosí, Veracruz and Yucatán, corresponding to 1362, 1860, 1713, 1447 and 1139 GDD, respectively, with varying base temperatures. Marcial et al. (2021) conducted a characterization in La Comarca Lagunera, identifying that maize emergence occurred at 300 GDD, vegetative development between 300 and 900 GDD, tassel formation between 900 and 1100 GDD, grain filling between 1100 to 1600 GDD, and finally, physiological maturity corresponded to 1600 a 1650 GDD. Corral-Ruiz et al. (2011) averaged historical GDD for the period 1961-2003, to reach maturity in maize, reporting a total of 2061 GDD for the states of Jalisco, Michoacán, Morelos, Puebla and Chiapas. Sifuentes-Ibarra et al. (2020) calculated GDD for an agricultural cycle over 20 years (1998-2018). In the Irrigation District 075 "Valle del Fuerte" located in Sinaloa, the lowest value occurred in the 2006-2007 cycle, accumulating 1226 GDD with an average temperature of 18.1 °C and a duration of 167 days, while the highest value occurred during the 2016-2017 cycle, with 1528 GDD at an average temperature of 20.1 °C and a duration of 147 days. Ruiz-Corral et al. (2002) calculated the average duration of the maturity cycle for the H311 maize hybrid across different locations in Zacatecas, reaching 1424 GDD at physiological maturity; based on this information, the maize hybrid can be classified as having an intermediate-to-late growth cycle.

Conclusions

Temperature is a key factor that directly or indirectly affects agricultural productivity, as it regulates the physiological processes within the plant. In maize growth, temperatures above the optimal range adversely affect the plant's physiological functions, root activity, flowering, grain filling, and overall yield. In contrast, low temperatures delay seed germination, reduce growth rates, and negatively affect the vigor of maize plants.

Growing Degree Days provide a relatively simple method for monitoring the physiological development of crops and for adjusting management practices to align with favorable conditions during the growing season. By using the GDD index, it is possible to identify the optimal timing for improving maize management practices, estimate seasonal growth and development, and predict crop growth, maturity, and yield.

It is recommended to use average GDD values, because they provide a baseline for understanding that significant variations can occur between location and across years due to changes in climate patterns. Furthermore, GDD serve as an indicator for assessing the impact of climate change on maize, since rising global temperatures are expected to increase the average GDD across different agricultural production areas. This change can create a natural imbalance in maize development, accelerating growth and potential resulting in either positive or negative effects on crop yield.

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