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GROWING DEGREE DAY: AN ESSENTIAL COMPONENT FOR SUSTAINABLE MANAGEMENT OF *Spodoptera frugiperda* (J E SMITH): A REVIEW

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ABSTRACT

Insects are exothermic organisms. Their phenology and behavior are affected by temperature. An amount of total heat unit accumulated to develop insect from one stage to another is expressed as growing degree day. Growing degree day has immense importance in integrated pest management which helps in predicting insect pest emergence, population growth and its distribution. Spodoptera frugiperda (J.E. Smith) *is a migratory invasive pest of maize which neither hibernates nor survive during winter in the hill of Nepal. Insect population survived in terai during winter season multiply in spring and migrate to hills of Nepal. Study in growing degree day required for different stages of S. frugiperda helps in forecasting the pest incidence aiding timely and sustainable management of this pest during maize cultivation in hill and terai regions. The objective is to summarize the available data on thermal constant and threshold temperature, synthesize degree day calculation methods and to develop strategic framework for management of S. frugiperda.*

Keywords: Growing degree days, polyphagous, poikilothermic, *Spodoptera frugiperda*, temperature

INTRODUCTION

Insects are poikilothermic as their body temperature vary in relation to the temperature of their surroundings. Therefore, any fluctuations in environmental temperature directly influence their survival (Skendzic et al., 2021). Fluctuation in environmental temperature exert both direct and indirect influences on insect population. The direct effects occur through alterations in physiological activity across developmental stages, dispersal dynamics, biological and phonological processes, and overall survival rate. Whereas the indirect effects are mediated through modifications in host plant phenology and activity, abundance, and efficacy of natural enemies within the ecosystem.

Accumulated heat energy required for development of ectothermic organism like insect is measured in a unit called growing degree day. More than 250 years ago, researcher stated the relationship between degree day and duration of development related to temperature, which

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helps to understand how poikilothermic organisms evolve as they rely on external temperature to regulate their body temperature affecting biochemical reaction. Therefore, studying how developments changes with temperature gives the idea of biology, ecology and evolution (Pedigo, 1996). Growing degree day helps to estimate the total amount of heat require to complete its each life cycle. It helps to calculate the number of generations in future as well as forecasting different stage which support in integrated pest management.

The objective for this narrative review paper is to summarize the available data on thermal constant and threshold temperature of each life stage of *S. frugiperda*. Synthesize different calculation methods of growing degree day and thermal units within agricultural meteorology. Support to develop the strategic framework for growing degree day driven pest forecasting and sustainable integrated pest management intervention of *S. frugiperda* in Nepal.

METHODOLOGY

The relevant information related to degree day, growing degree days, methods for their calculations was collected thorough the study of published literature in the national and international journals, proceedings, books, reports, factsheets, and bulletins. Literature search was conducted using academic database including Google Scholar, Research Gate, Oxford Academia, SPRINGER NATURE, Science Direct, Nep Jol, ELSEVIER, Indian journals, PlOS One, books. Search study involved use of relevant keyword. The source was evaluated on the basis of credibility and related to research objective. The research findings were systematically summarized in both tabular and textual formats. It is a narrative review based on a qualitative summary of literature research on growing degree day. It serve as background for research paper and provide a review of a topic, integrating theoretical perspective.

RESEARCH DESIGN

This study outline as a comprehensive narrative review paper which include historical data, mathematical formula framework and entomological research finding. It relies on systematic compilation and collection of previously published peer- reviewed literatures. It lacks primary field experiment data or raw meta-analytical statistical testing.

KEYWORD

Primary keyword used during literature search include growing degree day, GDD, thermal unit, heat accumulated, *Spodoptera frugiperda*, Faw, fall armyworm, Lower development threshold, LDT, pest forecasting, climate change, temperature, insect migration, maize crop, insect phenology, history, insect development, insect stages and other keywords related to the study.

LITERATURE SEARCH PROCESS AND DATABASE

The literature on growing degree day and related topics was conducted over a period of six months till 2026. Literature review focused on examining research throughout a period of time, starting with the first time an issue, concept emerged in the literature, then tracing its evolution within the discipline till 2026. Relevant literature published between 1855 and 2026 were reviewed to gather information related to growing degree day. In order to maintain the quality of work peer-reviewed journal articles and book chapters were included and information from predatory journals, opinion pieces and unpublished raw data were not included.

RESULTS

DEGREE DAY AND GROWING DEGREE DAY

Global warming has increased the average surface temperature by 0.74 ± 0.18^{0}C in the time of 100 years, which has impacted both human activities and natural ecosystems (IPCC, 2007). Degree days are expressed as heating degree day (HDD), cooling degree day (CDD) (Moustris et al., 2011), and growing degree day (GDD) (Sadiq et al., 2025). Heating degree day and cooling degree day helps in analyzing weather related energy consumption (Lee at al., 2014). Heating degree day and cooling degree day represents the cumulative difference between the base temperature and outdoor air temperature over a specified period, used in the energy sector to estimate energy required for heating and cooling buildings (Moustris et al., 2011). Growing degree days and growing degree unit are synonyms and frequently used to assign a heat value accumulated in each day to relate growth and development of living organism (Fraisse et al., 2010; Sadiq et al., 2025). The French scientist Rene A. F. de Réaumur introduced the concept of growing degree days related to growth and development with respect to air temperature in 1730 (McMaster and Wilhelm, 1997). Since then, growing degree day has been used in biological system to predict the different growth stages of living organism (McMaster and Smika, 1988). According to Tarun and Bhanu (2022) degree day is a unit that combines temperature and time to predict the growth and development of an organism from one stage into another stage of its life cycle. Linear relationship is used to determine the relationship between development rate and temperature (Chander et al., 2023). Linear regression helps to calculate lower development threshold. Lower development threshold (LDT) is the temperature at which development of insects stops (Honek, 1996). One degree-day represents, one degree above the lower developmental threshold in 24 hours of period (Tarun and Bhanu, 2022).

HISTORY OF GROWING DEGREE DAY

Growing degree day has served as the foundation for calculating heat units to describe the relationship between temperature and development rate. Various models to predict the effect of temperature on plant growth and development came into existence soon after introduction of concept on thermal unit by French scientist Reaumur in 1730. Subsequently several methods for calculating heat units were successfully applied in agricultural sciences (McMaster and

Wilhelm, 1997). Traditionally, farmers often used the calendar based prediction of plant development for management decision which has limitations in predicting the accurate stage of plant growth. Growing degree day is an effective tool which measures heat accumulation over time, calculated using daily temperature data. Because plant development is directly driven by temperature rather than calendar dates, growing degree day models provide a much more accurate prediction of crop stages viz, emergence, flowering, maturity, harvesting. Thus, the growing degree day calculated from actual temperature data provides accurate tool for predicting the timing of accurate growth stage (Miller et al., 2001). Emphasis was given to temperature and degree day calculation methods based on weekly temperature developed during 19th and 20th centuries, although conflict existed among researchers on role of other weather parameters on degree day calculations in addition to temperatures (Gregory, 1954). Cooling and heating were also used to calculate energy requirement for cooling and heating in building sector based on hourly air temperature data (Moustris et al., 2011). Later on, De Candolle (1855) introduced this concept into geobotany, geographical distribution of climate related with temperature. Gregory (1954) mentioned about the use of degree day calculation in agricultural meteorology. In the early 1950's a growing degree day concept was widely adopted by canning industry to predict crop development rate on the basis of accumulated thermal rate (Neild and Seeley, 1977).

USES OF GROWING DEGREE DAY IN AGRICULTURE

Growing degree day has been used in predicting plant stages (Miller et al., 2001). It helps in the prediction of insect development and its activity which helps in the pest management (Herms, 2004). Degree day models help to predict the effect of climate change on the intensity, distribution and timing of the transmission of infectious diseases (Moore et al., 2012). It helps to forecast pest emergence and population growth (Abduljaleel et al., 2025). It also supports in time specific crop management decisions such as nutrient and pesticide applications and weed control (Sadiq et al., 2025). According to Miller et al. (2001), accumulated degree day is calculated from the starting date from a specific point in time known as biofix. Biofix is chosen based on key biological events that signal the beginning of the organism development. Selecting an appropriate biofix allows for more accurate prediction of developmental stages and improves the timing of management decisions. Degree day helps to estimate the developmental timing of an organism to schedule field activities more efficiently. It minimizes conflict between temporal overlap of cultural operations such as irrigation and pesticide application for the pest management. Coordinated cultural practice minimizes operational conflicts and improves overall pest management efficiency. It helps to forecast the pest, it determines the best time to apply the control measures, monitoring the pest activity over the season. Pest data collected along with degree day information helps to quantify pest biology under different temperature condition and its relationship to crop yield (Zalom et al., 1983). Calculating the insect development time with respect to time become the important tools in predicting insect for pest management (Roy et al., 2002). Although the growing degree day has many uses in agriculture, its study is limited in Nepal. A study was conducted to develop a model to predict different growth stages in grapevine (Acharya et al., 2025). So far study based on growing degree day focusing insect pest and management is lacking in Nepal.

GROWING DEGREE DAY AND EFFECTS IN INSECT PESTS

Temperature can easily change the phenotypic character affecting the various life history traits of insects (Atkinson, 1994). According to Kuo et al. (2006) elevated temperature influences the longevity, population dynamics and fecundity rate of insects. Proper amount of heat units can provide a reliable means to growth and development of many insect pests (Marchioro and Foerster, 2011). Biochemical and physiological process such as enzyme activity, tissue function operates most efficiently in the optimal temperature in most of the insects enzyme activity is also influenced by temperature for example digestive enzymes has maximum activity at 35-45^{0}C temperature. Beside that thermoregulatory behavior of insects (Chapman, 1969) also known to be affected by temperature.

RELATION OF TEMPERATURE AND DEGREE DAY

A rational relationship between temperature and degree day statistics is need to understand in order to use it; the heating degree day. Degree day cannot be obtained by applying arithmetical procedure because of heterogenous nature of temperature (Thom, 1954). Calculation of degree day is affected by the frequency of temperature measured over time. Higher temporal resolution more accuracy while lesser resolution has less accuracy. Degree day calculation based on hourly temperature provides better estimates than the daily and monthly temperature (Mourshed, 2012). According to Schoenau and Kehrig (1990) degree day calculation is based on assumption that the daily average temperature distribution is in a normal pattern over a month. According to Thom (1954) mean degree days cannot be derived from mean temperature alone, instead the standard deviation of temperature must also be considered because temperature variability strongly influences the frequency and magnitude of degree days. His study provided a reliable method for converting temperature normal into degree-day normal, forming a foundation for consistent climatological analysis. Different methods of degree day developed based on degree day probability are derived from the temperature distribution.

FALL ARMYWORM (*Spodoptera frugiperda*) INVASION

The fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) is a destructive global pest which causes serious threat to agriculture. It is a polyphagous pest, and maize is a preferred host (Prasanna et al., 2018). The fall armyworm is native to American continents (Luginbill, 1928). The insect was reported for the first time out of American continent Africa in 2016 (Goergen et al., 2016) and subsequently form Asia Karnataka, India in May 2018 (Sharanabasappa et al., 2018). The pest was recorded for the first time in Nepal from Gaindakot of Nawalpur district in May 2019 (Bajracharya et al., 2019). Since then, it has spread in most parts of Nepal causing havoc to maize production and plant infestation recorded up to 56% in winter and spring maize (Bajracharya et al., 2020).

ECONOMIC IMPACT OF FALL ARMYWORM (*Spodoptera frugiperda*)

Fall armyworm, *S. frugiperda* has been reported to cause substantial yield losses in maize. The pest can attack all stages of maize crop from vegetative to reproductive phase, with higher damage in vegetative stage (Prasanna et al., 2018). Hruska and Gladstone (1988) reported a yield reduction up to 45% due to *S. frugiperda* infestation in maize. Chimweta et al., (2020) observed that damage caused by second and third instar larvae of *S. frugiperda*, affecting leaves, silks, and tassels at infestation levels of 25-50%, resulted in a 58% reduction in maize grain yield. Furthermore, yield losses ranging from 15 to 73% were observed when 55-100% of plants were infested during the mid to late whorl growth stages (Hruska and Gould, 1997).

FALL ARMYWORM (*Spodoptera frugiperda*) IN MAIZE GROWING REGIONS

Nepal consists of three ecological regions, high-hills, mid-hills and terai based on topographical perspective. Maize producing areas consists of flat land of the terai (up to 800 m), mid-hill (800-1800 m) and high-hills (above 1800 m). Maize is produced in areas up to 2500 m. Temperature also varies in these three ecological regions in different period, on an average mid-hills are 5-8^{0}C cooler than the terai and 3-8^{0}C warmer than the high hills (Paudyal et al., 2001). *S. frugiperda* recognized as economically important pest of maize which could survive well in temperature 28-30^{0}C. Climate change can cause significant influence in geographic spread of insect pest. *S. frugiperda* took long distance seasonal migration moving in response to the temporal availability of favorable habitat that emerge at different time along its migration route (Gao et al., 2025). Maize cultivation across varying elevations and planting schedules creates a temporal and spatial continuum of host availability, which facilitates *S. frugiperda* migration by providing successive food resources along its migratory range. According to Bajracharya et al. (2020) fall armyworm can survive in winter season in terai and inner terai districts of Nepal where maize crop is cultivated. Foster and Cherry (1987) reported eggs of fall armyworms were most tolerant to cold temperature even surviving at -10^{0}C. The average minimum temperature during winter in high-hill and mid-hills of Nepal is recorded as -0.2^{0}C and 5.8^{0}C respectively, which is quite below developmental threshold (10.9^{0}C) of *S. frugiperda*. However, average minimum temperature during winter in terai region (10.3^{0}C) is quite comparable to the developmental threshold of *S. frugiperda*. Thus, fall armyworm could easily survive in terai region of Nepal during winter season and which could multiply as soon as the spring starts as average minimum temperature during spring is recorded 19.5^{0}C in terai which is quite higher than developmental threshold (DHM, 2017). Thus, adult population of fall armyworm from terai could migrate to hilly regions of Nepal as soon as the temperature become suitable for its growth and survival in hilly areas.

DEGREE DAY REQUIREMENT OF FALL ARMYWORM (*Spodoptera frugiperda*)

The biological development of *S. frugiperda* in relation to degree day accumulation provides information about the key physiological events from egg hatching to adult emergence. *S. frugiperda* requires accumulation of 462.43 growing degree days for emergence of adult from egg stage. Once 462.43 growing degree days reached effective monitoring can be scheduled for its management (Ashok et al., 2022). For the survival of *S. frugiperda* air temperature plays a vital role in regulating its life cycle and development rate is faster in warmer weather (Sumila et al., 2004). *S. frugiperda* does not survive in cold temperature and adult stage are more susceptible to cool temperature (Foster and Cherry., 1987). Adult survival decreases when exposed to temperature 9^0C or below. Indirect chilling began after reaching temperature of 15^0C (Tanaka and Matsukura, 2023). So, it migrates from unfavorable condition to favorable condition as it has strong migratory capacity (Prasanna et al., 2018). It lacks diapause behavior so temperature exerts a great influence on its population dynamics by regulating the metabolic activity and development rates and determines the degree of crop damage (Yan et al., 2022). Degree day required for each stage of life cycle of *S. frugiperda* were calculated as 35.68± 0.22 degree day for eggs, 204.60±123 degree days for larva, 150.54±0.93 degree days for pupa and 391.61±1.42 degree days for egg to adult development (Plesis et al., 2020).

GROWING DEGREE DAY REQUIREMENT FOR OTHER INSECT PESTS

Insect development is influenced by the temperature they exposed. Each species has a specific temperature below which no noticeable development takes place is its threshold development. The total amount of heat required over time for an insect to complete a stage of development is referred as its thermal constant (Andrewartha and Birch, 1954; Bursell, 1964). Threshold development and the thermal constant considered as useful indicators of an insect's potential distribution and abundance (Messenger 1959; 1970). Wilson and Barnett (1983) studied the thermal requirements for completion of cotton bollworm (*Heliothios zea*, Boddie) larval development at four constant temperatures of 60, 65, 70, and 80^0F and estimated as 572, 539, 622, and 583 degree-days, respectively.

Similarly, Jallow and Matsumura (2001) studied the effect of constant range of temperature 13.3 to 32.5^0C on the development of all life stage of *H. armigera* reared on tomato plant. The duration of the different stage of the life cycle decreased as temperature increased from 13.3 to 32.5^0C. The reported egg development required a thermal constant of 51 degree-days above threshold of 10.5^0C, while for the larval and pupal stages needed 215.1 and 151.8 degree days above their respective development threshold of 11.3^0C and 13.8^0C.

Ali et al. (1990) studied the effect of temperature on *S. frugiperda* reared in artificial diet at seven constant temperatures ranging between17-38^0C. They found variations in developmental rates, survival, pupal weights, and number of instars among different diets and temperatures. Eggs hatched in all temperature and larvae completed development except at 38^0C temperature. Larval and pupal development rate declined at temperature between 33 and 35.5^0C. Number of instars found to be increased when temperature was dropped below 25^0C simultaneously, increasing development time with increase in number of instars.

ACCUMULATED DEGREE DAY AND THERMAL CONSTANT

Different studies were conducted over a range of temperatures to estimate the threshold temperature and degree-day requirements for various developmental stages of *S. frugiperda* on maize, its major host crop, as well as on other host plants. Research has also been carried out to determine the threshold temperature of *Spodoptera litura* (Fab.) on groundnut and jute. In these studies, threshold temperature and thermal constants (degree days) were calculated using a linear regression model expressed as y = a + bx. From this equation, the lower developmental threshold temperature (t_0) was derived as –a/b (^{0}C), and the thermal constant (K) was subsequently calculated. Growing degree days required for various development stages of *S. frugiperda* and *S. litura* has been calculated by different researches, some of the research findings are presented in Table 1.

Table 1: Accumulated degree day and thermal constant of *S. frugiperda and S. litura*

S N	Insect	Crop	Temperature (^{0}C)	Threshold temperature (t_o)	Growing degree day				Reference
					Egg	Larva	Pupa	Adult	
1	*S. frugiperda*	Maize (*Zea maize*)	32	10.9	63	247.08	214.38	232.52	Ashok et al., 2022
2	*S. frugiperda*	Maize (*Zea maize*)	20-30	Egg:15.79 Larva:10.39 Pupa:14.05	30	360.2	129		Dahi et al., 2020
3	*S. frugiperda*	Turnip (*Brassica campestris*)	15 - 35	Egg: 11.14 Larva: 10.50 Pupa:10.90	55.76	225.50	133.31		Ouda et al., 2022
4	*S. frugiperda*	Maize (*Zea maize*)	18 - 36	Egg: 12.59 Larva: 12.33 Pupa: 12.67	45.45	333.33	166.67		Aggarwal. Et al., 2023
5	*S. frugiperda*	Sweet corn (*Zea maize*)	21 - 32	Egg:13.01 Larva: 12.12 Pupa:13.06	35.73	202.60	150.29		Plessis et al.,2020
6	*S. litura*	Jute (*Corchorus alitorius)*	18-32	Egg:11.93 Larva:10.68 Pupa:9.54	34.48	344.82	163.93		Thakur et al.,2017
7	*S. litura*	Groundnut (Arachis hypogea)	15 - 37	Egg:8.2 Larva:10 Pupa:10	64	303	155		Rao et al., 1989

Accumulated growing degree day has importance in development of maize to attain various stages of vegetative and reproductive stages. Early and full season maize varieties are known to differ in their duration and accumulated growing degree days (GDD). Generally, early- season, mid-season and full season maize varieties maturity days and accumulation GDD are presented in Table 2 and 3. Normally, maize plant develops above the threshold of base temperature 50^0F (10^0C) in warm season field corn (Ralph and James, 2026). Similar threshold temperature of *S. frugiperda* (10.9^0C) has been reported (Ashok et al., 2022). The minimum threshold temperature for development of maize as well as *S. frugiperda* is quite similar. Hence, accumulated heat units for both maize and *S. frugiperda* are nearly similar during maize growing season, thereby, *S. frugiperda* infestation occurs few days after maize seed emergence. *S. frugiperda* damage starting from early leaf initiation up to the tasseling/silking stage is considered to reduce yield significantly. *S. frugiperda* hatch eggs after accumulation of 30 GDD, and one complete generation of FAW requires about 500 GDD (Dahi et al., 2020). Maize remains in the field for a long duration and *S. frugiperda* begins damaging the crop soon after egg hatching. Since maize accumulates 2100–3200 GDD to mature the crop depending upon the variety, *S. frugiperda* could complete more than one generation during vegetative stage and multiple overlapping generations could occur during single maize growing season.

Table 2: Hybrids corn representing days and GDD from planting to harvesting of the central part of cornbelt of U.S. (Ralph and James, 2026)

SN	Corn	Days	GDD
1	Early season	85-100	2100-2400
2	Mid season	101-130	2400-2800
3	Full season	131-145	2900-3200

Table 3: Growth stage of corn with approximate GDDs and Cumulative GDDs (CFAES, 2026)

	Growth stage	Approximate GDDs	Cumulative GDDs
-	Planting	0	0
VE	Emergence	100	100
V3	Three -leaf collar	246	346
V6	Six -leaf collar	246	592
V9	Nine-leaf collar	246	838
V12	Twelve -leaf collar	182	1020
V15	Fifteen -leaf collar	150	1170
V19	Nineteen- leaf collar	50	1370
VT	Tasseling	50	1420
R1	Silking	-	1420
R2	Blister	266	1686

	Growth stage	Approximate GDDs	Cumulative GDDs
R3	Milk	144	1830
R4	Dough	151	1981
R5	Dent	343	2324
	Dent-$^{1/2}$ milk line	-	-
R6	Black layer	326	2650

METHODS OF DEGREE DAY CALCULATION

Temperature changes from year to year over an entire growing season, there may be either increase or decrease in temperature than the normal during any period of growing season. Growing degree day is a method of assigning heat value of each day. Summation of value of each day gives an estimate of total heat required by an organism for their development and growth (Miller et al., 2001). Generally, three methods are applied for calculating degree day, they are the average method, the modified average method, and the triangle and sine wave methods (Herms, 2004).

Average method: The simplest method of calculating the number of daily degree day. It is calculated by subtracting the lower threshold temperature from the average daily temperature. The basic equation for the calculation of degree days is given by McMaster and Wilhelm (1997).

$$DD = \frac{T_{max}+T_{min}}{2} - t_o$$

Whereas,

DD = degree days

T_{max} = daily maximum temperature

T_{min} = daily minimum temperature

t_o = lower threshold temperature

One of the drawbacks of this method is, it neglects the daily minimum temperature that fall below the species lower temperature threshold. This situation mainly occurs in spring which results in underestimation of degree days accumulated by insects as not all hourly temperature during a day are above the threshold level. During this period also insect development continues but heat accumulation systems fail to account for it.

Modified average method: This method corrects the weakness of the average method; daily minimum temperature is substituted with lower threshold temperature. This method is used when the minimum temperature drops below the lower threshold temperature. Thus, this approach approximates reality more closely by calculating the daily temperature accumulation between the maximum temperature and lowest threshold related to the species,

$$DD = \frac{T_{max}+ t_o}{2} - t_o$$

Whereas,

DD = degree days

T_{max} = daily maximum temperature

t_o = lower threshold temperature

This shows higher number of degree days by including the development taken during the short periods in which temperature is slightly above the lower development threshold.

Triangle and sine wave method: Above two methods of growing degree day calculation do not consider the daily fluctuation of temperature within 24 hours. In order to correct the problem of daily temperature fluctuation and pattern some methods were proposed by various workers viz. simple triangle, double triangle, simple sine and double sine methods. These methods assume that the minimum daily temperature occurs at midnight and daily maximum temperature occur at noon. These methods also allow incorporation of upper threshold temperature above which insects do not develop.

Triangle method: In this method degree day is estimated as the area within the triangle and between the lower and upper threshold temperatures. There are two types of triangle methods proposed by various workers:

a. *Single triangle method*: Lindsey and Newman (1956) calculated degree day estimating the area under the temperature curve using as simple triangle. This method is based on assumption the temperature curve is symmetrical around the maximum temperature within 24 hours.

b. *Double triangle method*: Sevacherian et al. (1977) made some modification in single triangle method, that the difference between the first and second daily minimum temperature may not be the same. As a result, it calculates the area under the curve on a half day basis as double triangle. The degree day are estimated as the areas within the triangles and between the thresholds which is the sum of the degree days for the two halves.

Sine wave method: Baskerville and Emin (1969) modified the triangle approach and calculated the degree including the value of development maximum and estimate using simple sine. This method assumes a sine wave pattern using daily maximum and minimum temperature with temperature fluctuation allowing both lower and upper threshold temperatures. This method represents the daily temperature pattern as sine wave, representing the gradual rise and fall of temperature over time. The area under the sine wave curve used to calculate the temperature accumulation. Later, Allen (1976) modified the technique and presented formulas and a computer program for its use. According to him formulas may vary to specific relationship between the daily minimum and maximum temperature and lower and upper threshold. According to his opinion, data could be classified into six possible situations, they are:

1. The minimum temperature is higher than the lower threshold and the maximum temperature is higher than upper threshold.
2. The minimum temperature is lower than the lower threshold and maximum temperature is higher than upper threshold.
3. Both maximum and minimum temperatures are within thresholds.
4. The minimum temperature is lower than lower threshold and maximum temperature is lower than upper thresholds.
5. Both minimum and maximum temperature are higher than the upper threshold.
6. Both minimum and maximum temperature are lower than lower threshold.

Generally, sine method produces a sine curve using the minimum and maximum temperature of the day. This method could be classified as:

a. Single sine method: In this method minimum temperature is same for both halves of the day and estimated heat accumulation in the area under the sine curve and between thresholds.

b. Double sine method: In method degree day is estimated by fitting two different sine curves for each half using minimum and maximum temperature (UC, IPM 2005).

According to Baskerville-Emin (1969), growing degree days could be calculated in different three cases with different methods which are as follows:

Case 1: If maximum temperature is less than base temperature

Growing degree day (GDD) for the day =0

Case 2: If minimum temperature is greater or equal to base temperature

Average Temperature (T_{AVE}) is calculated then,

GDD = Average Temperature (T_{AVE}) – Base Temperature (BASE)

Which is similar to average method calculation.

Case 3: If minimum temperature is lower than base temperature and base temperature is lower than maximum temperature

$$GDD= ((W*COS (A)) – ((BASE-T_{AVE}) * ((3.14/2)-A)))/3.14$$

Whereas,

$$W = \frac{T_{max} - T_{min}}{2}$$

$$A= Arcsin ((BASE- T_{AVE})/W)$$

$$T_{AVE} = \frac{T_{max}+T_{min}}{2}$$

T_{min} = minimum temperature

T_{max}= maximum temperature

BASE=.Base temperature

CALCULATION OF DEVELOPMENTAL THRESHOLD AND DEGREE DAY IN INSECT

Degree day in insect is generally calculated on the basis of lower developmental threshold and accumulated heat units at constant temperature. According to Dahi et al. (2020) theoretical development thresholds (t_o) and the accumulated thermal units (K) is calculated using the regression formula:

$y = a + bx$

$t_o = - a/b$

$K=1/b$

Whereas,

y = development rate of a given stage

x = temperature in degree centigrade

a = constant term

b = regression coefficient

t_o= lower threshold of development and

K =Thermal unit

While the mean number of degree days (^{0}D) required for the development of the egg, larval, pupal and pre-embryogenic period at constant temperature can be estimated using the equation proposed by Jackson and Elliott (1988) as follows:

GDD (^{0}D) = $T(C-T_o)$

Whereas,

GDD = Growing degree day

^{0}D = unit of degree day

T = number of days taken to complete development at a constant temperature

C= constant temperature

t_o = minimum developmental threshold temperature

Previously Campbell et al. (1974) proposed simple linear regression analysis to determine the relationship between temperature and the development rate. The lower threshold temperature and the number of degree days required to complete the development of each of the stages, as well as their standard errors, were calculated using the equation:

$y = a+bx$

Whereas,

y=1/days, x= temperature, a= intercept and b= slopes

In this method lower threshold temperature was estimated by setting y = 0 and solving x from the regression equation. Similarly, the lower temperature threshold was calculated as $t_o = -a/b$ and the thermal constant for development in number of degree days (^{0}D): k=1/b.

The degree day required for different stages under field condition can be calculated on the basis of thermal summation scheme proposed by AliNiazee (1976). The daily minimum and maximum temperature recorded at field condition is used along with previously determined lower threshold temperature in this procedure:

$$DD = \frac{\text{Daily max. temperature + daily min. temperature}}{2} - \text{lower threshold temperature}$$

Time required for development decreased with increasing temperature, the total amount of heat needed to complete the development remains approximately same (Wilson and Barnett, 1983). According to them degree days (^{0}D) is the heat accumulation between the temperature and the lower threshold multiplied by total days to develop which can be expressed mathematically:

$^0D = (C-t_o)$ X days to develop

C = Constant temperature

t_o = Lowe threshold temperature

IMPLICATION OF GROWING DEGREE DAY IN FALL ARMYWORM *(SPODOPTERA FRUGIPERDA)* MANAGEMENT

S. frugiperda life cycle is strongly dependent on temperature, degree day model estimates the amount of heat required to complete each life cycle. Growing degree days helps to determine the number of generation of *S. frugiperda* (Sumila et al., 2024). *S. frugiperda* start damaging from early leaf initiation upto silking /tasseling stage and reduce the maize yield. *S. frugiperda* require about 500 degree day (Dahi et al., 2020) while maize accumulates 2100-3200 degree days (Ralph and James, 2026) to mature. So *S. frugiperda* complete more than one generations during vegetative stage and multiple generation could occur during single maize growing season. The study of growing degree day in *S. frugiperda* helps in understanding the biological development of insects over a period of time and physiological events like scouting, placement of traps and timing for damage observation in addition to the control of damaging larval stage by scheduling the insecticide spray. Degree day study support in predicting the different life stages of *S. frugiperda* which helps in planning pest management operations like release of biological control agents and application of microbial insecticides for effective management of the pest which helps in reducing the unnecessary chemical hazard, minimize environmental impact and cost of cultivation.

DISCUSSION

Insects are exothermic organism so its physiological processes are largely depended on temperature. Growing degree day helps to quantify heat accumulation for insect development. *S. frugiperda* development is regulated by thermal accumulation thus degree day could be used to predict its occurrence and seasonal activity which ultimately helps in management. It also supports in crop management decision such as pesticides application (Sadiq et al., 2025).

Linear relationship between temperature and insect development rate which form the basis for estimating lower development threshold and thermal constants of insect. On the basis of various literatures reviewed lower development threshold of different developmental stages of *S. frugiperda* ranged from 10.4^{0}C to 15.8^{0}C. Similarly, thermal requirement to develop FAW eggs into adult ranged between 390 to 500 degree days. Such findings indicate that *S. frugiperda* required a predictable amount of heat to complete its development. Insect stages occurred in the fields could be predicted, if developmental threshold and thermal requirement could be determined for *S. frugiperda* in Nepal. Insect management tactics could be chosen based on stage of insect which differs in feeding habits and vulnerabilities. Such method to predict insect developmental stage based on degree day and its management at appropriate time had been successfully used by Hems (2004). Aggarwal et al. (2023) calculated the degree day for planning the most effective period for monitoring and effective suppression to reduce the losses occurred by *S. frugiperda*.

Despite of increasing damage and losses caused by fall armyworm in Nepal, information on degree day accumulation, thermal requirement and seasonal generation dynamics under Nepalese agro-ecological conditions still lacking. Nepal has diverse topography and variation in temperature in different topographic region play a crucial role in determining population dynamics and geographical distribution of *S. frugiperda*. The pest can tolerate wide range of temperature but its development is constrained when temperature fall below the lower development threshold of approximately 10.9^{0}C as mentioned by Ashok et al. (2002). In Nepal average winter temperature in hilly region are below threshold, which limits the continuous development and survival of the pest but in terai region temperature remains close to the development threshold, creating favorable condition for its survival and serve as inoculum source for hills (Bajracharya et al., 2020). Growing degree day model could be valuable tool for predicting temperature driven migration and population development of *S. frugiperda* which helps in development of pest forecasting system. Location specific degree day forecasting model could also provide an effective decision support tool for integrated *S. frugiperda* management program and contribute to sustainable production of maize Nepal.

CONCLUSION

Degree days and thermal constant required for the growth and development of the pest can be exploited for effective integrated management of *S. frugiperda* by predicting its occurrence in the field. Despite its importance, application of growing degree day for insect pest management remain unexplored area of entomological studies in Nepal. Studies on degree day calculation including thermal constant and developmental threshold for *S. frugiperda* or any other insect pests under laboratory and field conditions within the country is lacking. Thus, scientific study on growing degree day of fall armyworm need to be conducted in future for its efficient management through early prediction and timely implementation of appropriate management practices for sustainable production of maize in Nepal.

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The author declare that they do not have conflict of interest that could influence the publication of this article.

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REFERENCES

Abduljaleel, H. Umirqulova, F., Bruno, M., Matyakubov,M., Paranthama, P., & D Kalidoss. D. (2025). Predicting pest outbreaks with a climate-insect interaction model based on degree-day accumulation. *Natural and Engineering Science, 10*(2), 315-325.

Acharya, A. K., Gautam, D.M., Khatri, B. B., Poudel, P.R., & Dahal, K.C. (2025). Degree day model of grapevine phenology in the mid-hill conditions of Nepal. *The Journal of Agriculture and Environment, 6*, 219-226.

Aggarwal, N., Jindal, J., Singh, P., Bhargav, O., and Sharma, K.P. (2023). Thermal idices of Spodoptera frugiperda (J.E.Smith) on maize in Northern India. *Indian Journal of Ecology,50*(6), 2065-2070. https://doi.org/10.55362/IJE/2023/4176.

Ali, A., Luttrell, R. G., & Schneider, J.C. (1990). Effects of temperature and larval diet on development of the fall armyworm (Lepidoptera: Noctuidae). *Annals of the Entomological Society of America, 83*(4), 725-733.

AliNiazee, M.T. (1976). Thermal unit requirements for determining adult emergence of the western cherry fruit fly (Diptera: Tephritidae) in the Willamette Valley of Oregon. *Environmental Entomology, 5*(3), 397-402.

Allen, J. C. (1976). A modified sine wave method for calculating degree days. *Environmental Entomology, 5*, 388- 396.

Andrewartha, H.G., & Birch, L.C. (Ed.). (1954). *The Distribution and abundance of animals*. (1st ed.). University of Chicago Press, Chicago and London.

Ashok, K., Balasubramani, V., Kennedy, J.S., Geethalakshmi, V., Jeyakumar, P., & Sathiah, N. (2022). Degree days and demography of *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) on maize at different temperatures. *Journal of Applied & Natural Science, 14*, 24 - 30. https://doi.org/10.31018/jans.v14iSI.356.

Atkinson, D. (1994). Temperature and organism size- A biological law for ectotherms. *Advances in Ecological Research, 25*, 1-58.

Bajracharya, A.S.R., Bhat, B., & Sharma, P. (2020). Spatial and seasonal distribution of fall armyworm, *Spodoptera frugiperda* (JE Smith) in Nepal. *Journal of the Plant Protection Society*, *6*, 192-201.

Bajracharya, A.S.R., Bhat, B., Sharma, P.N., Shashank, P.R., Meshram, N.M., & Hashmi, T.R. (2019). First record of fall armyworm *Spodoptera frugiperda* (J.E. Smith) from Nepal. *Indian Journal of Entomology, 81(*3), 635-639. https://doi:10.5958/0974-8172.2019.00137.8.

Baskerville, G.L., & Emin, P. (1969). Rapid estimation of heat accumulation from maximum and minimum temperatures. *Ecology, 50*(3), 514-517.

Bursell, E. (Ed.) 1964. Environmental aspects: temperature. In: The Physiology of Insecta Vol.4. (M. Rockstein, Ed). Academic Press, New York and London; pp. 283-321.

Campbell, A., Frazer, B.D., Gilbert, N., Gutierrez, A.P., & Mackauer, M. (1974). Temperature requirements of some aphids and their parasites. *Journal of Applied Ecology, 11*, 431–438.

CFAES. (2026, February 3).Corn growing degree days: A method of maturity rating for hybrids. (AGF-0101). Ohio State University. https://ohioline.osu.edu/factsheet/agf-101.

Chander. S., Husain. M., & Baradevanal, G. (2023). Determination of Thermal constants and developmental thresholds for gram pod borer, *Helicoverpa Armigera* (Hübner) (Lepidoptera: Noctuidae). *Hexapoda, Insecta Indica*, 30(1and 2), 1-8. http://org/10.55446/hexa.2023.581

Chapman, R.F. (Ed.).1969. The insects: structure and function. (4th ed.) Cambridge University PFress. United Kingdom.

Chimweta, M., Nyakudya, I.W., Jimu, L, & Mashingaidze, A.B. (2020). Fall armyworm [*Spodoptera frugiperda* (JE Smith)] damage in maize: Management options for flood-recession cropping smallholder farmers. *International Journal of Pest Management, 66*(2), 142-154. https://doi.org/10.1080/09670874.2019.1577514

Dahi, H.F., Salem, S.A., Gamil, W.E., & Mohamed, H.O. (2020). Heat requirements for the fall armyworm *Spodoptera frugiperda* (JE Smith)(Lepidoptera: Noctuidae) as a new invasive pest in Egypt. *Egyptian Academic Journal of Biological Sciences A Entomology, 13*(4), 73-85. http://org/10.21608/eajbsa.2020.120603

De Candolle, A. (1855). Géographie botanique raisonnée: ou, Exposition des faits principaux et des lois concernant la distribution géographique des plantes de l'époque actuelle (Vol. 2). V. Masson.

DHM. 2017. Observed climate trend analysis of Nepal (1971-2014). Department of hydrology and meteorology, Ministry of population and environment, Government of Nepal. https://www.dhm.gov.np/uploads/dhm/climateService/Observed_Climate_Trend_Analysis_

Report_2017.pdf

Foster, R.E., & Cherry, R.H. (1987). Survival of fall Armyworm, *Spodoptera frugiperda, (*Lepidoptera: Noctuidae) exposed to cold temperatures. *Florida Entomologist*, 70(4), 419-422.

Fraisse, J., Bellow, J., & Brown, C. (2010). Degree days: Heating, cooling, and growing. University of Florida UFAS Extension ABE 381/AE428. https://doi.org/10.32473/edis-ae428-2007.

Gao, F.Q., Chen, H., Kyerematen, R., Hu, G., Early, R., & Chapman, J.W. (2025). High migratory potential of fall armyworm in West Africa despite stable temperatures and widely available year-round habitats. *Insect Science*, 1-12. https://doi.org/10.1111/1744-7917.13502.

Goergen, G., Kumar, P. L, Sankng, S.B., Tagola, A., & Tamo, M. (2016). First report of outbreak of fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae), a new alien invasive pest in west and central Africa. *PLOS ONE*, 1-9. 2016. https://doi.org/10.1371/journal.pone.0165632

Govind K.C., Karki T.B., Shrestha J, & Achhami B.B. 2015. Status and prospects of maize research in Nepal. *Journal of Maize Research and Development,* 1(1), 1-9.

Gregory, S. (1954). Accumulated temperature maps of the British Isles. *Transactions and Papers Institute of British Geographers*, 20, 59-73.

Herms, D. A. (2004). Using degree-days and plant phenology to predict pest activity. In V. Krischik & J .Davidson (Eds.). *IPM of Midwest landscape* (pp. 49-59). University of Illinois.

Honek., A. (1996). Geographical variation in thermal requirement for insect development. *European Journal of Entomology, 93*(3), 303-312.

Hruska, A.J., & Gould, F. (1997). Fall armyworm (Lepidoptera: Noctuidae) and *Diatraea lineolata* (Lepidoptera: Pyralidae): Impact of larval population level and temporal occurrence on maize yield in Nicaragua. *Journal of Economic Entomology, 90*(2), 611-622.

Hruska. A.J., & Gladstone. S.M. (1988). Effect of period and level of infestation of the fall armyworm, *Spodoptera frugiperda,* on irrigated maize yield. *Florida Entomologist, 71*(3), 249-254.

IPCC. (2007). Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report. Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability. Summary for Policymakers. Brussel, Belgium.

Jackson, J.J., & Elliot, E.C. (1988). Temperature-dependent development of immature stages of the western corn rootworm, *Diabrotica virgifera* (Coleoptera: Chrysomelidae). *Environmental Entomology, 17*, 166-171.

Jallow, M. F., & Matsumura, M. (2001). Influence of temperature on the rate of development of *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae). *Applied Entomology and Zoology, 36*(4), 427-430.

Kuo, M.H., Chiu, M.C & Perng, J.J. (2006). Temperature effects on life history traits of the corn leaf aphid, *Rhopalosiphum maidis* (Homoptera: Aphididae) on corn in Taiwan. *Applied Entomology and Zoology, 41*(1), 171-177.

Lee, K., Baek, H. J., & Cho, C. (2014). The estimation of base temperature for heating and cooling degree-days for South Korea. *Journal of Applied Meteorology and Climatology*, *53*(2), 300-309.

Lindsey, A. A., & Newman, J.E. (1956). Use of official weather service data in spring time: temperature analysis of an Indiana phenology record. *Ecology, 37*, 812-823.

Luginbill, P. (1928). The fall armyworm. USDA Technical Bulletin 34:1:91.

Marchioro, C.A. & Foerster, L.A. (2011). Development and survival of the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Yponomeutidae) as a function of temperature: effect on the number of generations in tropical and subtropical regions. *Neotropical Entomology, 40*, 533 -541.

McMaster, G. S., & Smika, D. E. (1988). Estimation and evaluation of winter wheat phenology in the central Great Plains. *Agricultural and Forest Meteorology, 43*(1), 1-18.

McMaster, G.S., & Wilhelm, W.W. (1997). Growing degree-days: one equation, two interpretations. *Agricultural and Forest Meteorology, 87*(4), 291-300.

Messenger, P.S. (1959). Bioclimatic studies with insects. *Annual Review of Entomology, 4*,183-206.

Messenger, P.S. (Eds.) (1970). *Bioclimatic inputs to biological control and pest management programs.* Concepts of Pest Management (R.L. Rabb. & F.E. Guthrie. Eds.). North Carolina State, University Press, Raleigh; pp. 84-99.

Miller, P., Lanier, W., & Brandt, S. (2001). Using growing degree days to predict plant stages. Cooperative Extension Service, Montana State University, Bozeman. Montguide MT200103 AG 7/2001.

MoALD. (2025). Statistical information on Nepalese agriculture 2080/81 (2023/24). Kathmandu: Ministry of Agriculture, and Livestock Development.

Moore, J.L, Liang, S., Akullian, A., & Remais, J.V. (2012). Cautioning the use of degree-day models for climate change projections in the presence of parametric uncertainty. *Ecological Applications, 22*(8), 2237-2247.

Mourshed, M. (2012). Relationship between annual mean temperature and degree-days. *Energy and Buildings, 54*, 418-425. https://doi.org/10.1016/j.enbuild.2012.07.024

Moustris, K. P., Zacharia, P. T., Larissi, I. K., Nastos, P.T., & Paliatsos, A. G. (2011). Cooling and heating degree-days calculation for representative locations within the greater Athens area, Greece. *Proceedings of the 12th International Conference on Environmental Science and Technology*, Rhodes, Greece. pp. 8-10.

Neild, R.E., & Seeley, M.W. (1977). Growing degree days predictions for corn and sorghum development and some applications to crop production in Nebraska. University of Nebraska, Lincoln, N libraries. Research Bulletin 280.

Ouda, M.I., Shalaby, H.H., Mousa E.A.M. (2022). Biology and life table of fall armyworm *Spodopterda frugiperda* (J.E.Smith) reared on turnip leaves in Egypt. *International Journal of Entomology Research, 7*(12), 62-69.

Paudyal, K.R., Ransom, J.K., Rajbhandari, N.P., Adhikari, K., Gerpacio, R.V., & Pingali, P.L. (2001). Maize in Nepal: Production systems, constraints, and priorities for research. NARC and CIMMYT, Kathmandu, Nepal.

Pedigo, L.P. (1996). Entomology and pest management. 2nd ed. Prentice Hall Inc., USA.

Plessis, H.D., Schlemmer, M.L., & Berg, J.V.D. (2020). The effect of temperature on the development of *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Insects. 11*, 228. https://doi:I0.3390/insectsl1040228.

Prasanna, B.M., Huesing, J.E., Eddy, R., & Peschke, V.M. (Eds.). (2018). *Fall armyworm in Africa: A guide for integrated pest management*. (1st ed.). Mexico, CDMX: CIMMYT. pp 108.

Ralph. E., and James, E. (2026, Feb-3). Climate and weather: Growing season characteristics and requirements in the corn belt. (NCH-40). Purdue University. Cooperative extension service. https://www.extension.purdue.edu/extmedia/nch/nch-40.htm.

Rao, G. R., Wightman, J. A., and Rao, D. R. (1989). Threshold temperatures and thermal requirements for the development of *Spodoptera litura* (Lepidoptera: Noctuidae). *Environmental Entomology*, *18*(4), 548-551.

Roy, M., Brodeur, J., & Cloutier, C. (2002). Relationship between temperature and developmental rate of *Stethorus punctillum* (Coleoptera: Coccinellidae) and its prey *Tetranychus mcdanieli* (Acarina: Tetranychi dae). *Environmental Entomology, 31*(1), 177-187.

Sadiq, A.A., Njiddari, G.E., & Musa, P.A. (2025). An overview of growing degree days and heat unit application in crop production. *International Journal of Agriculture and Earth Science, 11*(80), 83-102. http://doi/10.56201/ijaes.vol.11.no8.2025.pg83.102

Schoenau, G.J., & Kehrig, R.A. (1990). Method for calculating degree-days to any base temperature. *Energy and buildings, 14*(4), 299-302. https://doi.org/10.1016/0378-7788(90)90092-W

Sevacherian,V., Stern, V.M., & Mueller, A.J. (1977). Heat accumulation for timing Lygus control measures in a safflower-cotton complex. *Journal of Economic Entomology, 70*, 399-401.

Sharanbasappa, S., Kalleshwaraswamy, C.M., Asokan, R., MahadevaSwamy, H.M., Maruthi, M.S., Pavithra, H.B, Hedge, K., Navi, S., Prabhu, S.T., & Goergen, G. (2018). First report of the fall armyworm, *Spodoptera frugiperda* (J E Smith) (Lepidoptera: Noctuidae), an alien invasive pest on maize in India. *Pest Management in Horticultural Ecosystem, 24(*1), 23-29.

Skendzic, S., Zovko, M., Zivkovic, I. O., Lesic, V., & Lemic, D. (2021). The impact of climate change on agricultural insect pests. *Insects, 12*(5), 440. https://doi.org/10.3390/insects12050440.

Sumila, T.C.A., Ferraz, S.E., & Durigon, A. (2004). Climate change impact on *Spodoptera frugiperda* (Lepidoptera: Noctuidae) life cycle in Mozambique. *PLOS Climate, 3*(1), 1-25. https://doi.org/10.1371/journal.pclm.0000325.

Tanaka, Y., & Matsukura, K. (2023). Quantitative effects of temperature and exposure duration on the occurrence and repair of indirect chilling injury in the fall armyworm *Spodoptera frugiperda*. *Insects, 14(*4), Article. 356. https://doi.org/10.3390/insects14040356.

Tarun, K., & Bhanu, V. (2022). Growing degree days. Phenology forecasting for crops. *Just Agriculture Multidisciplinary E-New letter*, 2(6),1-4. (e-ISSN:2582-8223) www.justagriculture.in.

Thakur, N., Gotyal, B.S., Selvaraj, k., and Satpathy, S. (2017). Effect on biology of jute indigo caterpillar, Spodoptera litura (Fabricius) under five different constant temperatures. *Journal of Entomology and Zoology Studies, 5*(4),102-2-106.

Thom, H.C.S. (1954). The rational relationship between heating degree days and temperature. *Monthly Weather Review, 82*(1), 1-6.

UC, IPM. (2005). How to manage pests: Degree days. California: Agriculture and Natural Resources, University of California. https://ipm.ucanr.edu/weather/ddconcepts.html.

Wilson, L. & Barnett, W. (1983). Degree-days: an aid in crop and pest management. *California Agriculture*, 37(1), 4-7.

Yan, X.R., Wang, Z.Y., Feng, S.Q., Zhao, Z.H., & Li, Z.H. (2022). Impact of temperature change on the fall armyworm, *Spodoptera frugiperda* under global climate change. *Insects, 13*(11), Article. 981. https://doi.org/ 10.3390/insects13110981

Zalom, F.G., Goodell, P.B., Wilson, L.T., Barnett, W.W., & Bentley, W.J. (1983). Degree-days, the calculation and use of heat units in pest management: University of California Division of Agriculture and Natural Resources. University of California, Berkeley, CA. Leaflet 21373.