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RESEARCH ARTICLE

# Rainfall variability and sowing window effects on maize genotype performance in Chamarajanagara district, Karnataka

**H P Rajath[1], C Kumar[1*], S R Inamdar[2], M Hanumanthappa[3], H R Bhanuprakash[1], Vishwanth V E[1], Kumar C V[4], Manjunath K[5], Navinkumar[6] & Kumar G V S[7]**

[1]Department of Agriculture, Amity Institute of Organic Agriculture, Amity University, Noida 201 313, Uttar Pradesh, India
[2]Department of Computer Sciences, University of Agricultural Sciences, Mandya 571 405, Karnataka, India
[3]Department of Agronomy, University of Agricultural Sciences, Raichur 584 104, Karnataka, India
[4]Department of Plant Pathology, Central Institute for Sub Tropical Horticulture, Lucknow 226 101, Uttar Pradesh, India
[5]Department of Geology, Government Science College, Chitradurga 577 501, Karnataka, India
[6]Department of Agricultural Extension, Mahatma Gandhi Udyanikee Evam Vanikee Viswavidyalaya, Durg Raipur 492 001, Chhattisgarh, India
[7]University of Agricultural Sciences, Mandya 571 405, Karnataka, India

*Correspondence email - ckumar@amity.edu

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## Abstract

The study explores the use of rainfall patterns and maize types in Chamarajanagara district, Karnataka, India, where rainfall varies significantly from place to place and year to year. The researchers used data from weather stations collected every month from January to December 2021 and tested 6 methods to create full maps: Inverse distance weighted (IDW), Spline, Natural neighbour, Trend, Kriging and Topo to Raster. The results show that weather plays a significant role in maize yields, with timing and amount playing a crucial role. Sowing windows or the best weeks to plant seeds, are crucial in this region, as planting too early or too late can lead to water stress. The hybrid MAH 14-5 genotype was found to be particularly effective when sown in the first week of July, resulting in stronger growth, higher nutrition levels and reduced anti-nutritional factors. These findings emphasise the importance of selecting the right planting time to maximise water use efficiency, harness soil conditions and utilise sunlight intensity. Farmers who match sowing to rain peaks can boost yields without extra inputs. The study also highlighted how rain changes over time and space in the district, with some spots experiencing steady showers in June and others experiencing heavy bursts in August, leading to uneven crop growth. Smart planning involves tailoring sowing windows to local rain forecasts, choosing genotypes that fit the area's weather and aligning tasks like fertilising or weeding with rainfall. These steps help farmers adapt and achieve reliable harvests year after year.

**Keywords:** interpolation techniques; maize genotypes; rainfall analysis; sowing windows; spatial variability

## Introduction

The rise in greenhouse gas emissions has led to increased air temperature, affecting global air circulation and causing changes in meteorological conditions. This has particularly affected the intensity and frequency of rainfall, posing greater risks to various input management practices in crop production and yield (1–2). Higher variability in agricultural production due to extreme climate variability has also been reported (3). Sustainable agriculture depends on the amount and distribution of rainfall, as excessive or insufficient precipitation hampers crop growth and agricultural activities by causing floods or droughts (4). Maize is the most widely cultivated and consumed cereal crop globally, contributing significantly to food security. Along with wheat and rice, it accounts for nearly half of the world's primary crop production. Owing to its high potential for both grain and fodder yield, maize holds a prominent place among cereals (5). In India, maize cultivation is becoming more prominent due to its versatility and adaptability to diverse agro-climatic conditions. Globally, maize is cultivated on nearly 201 million tonnes hectares of land, producing 1162 million tonnes with a productivity of 5754.7 kg/ha (6). In 2023-24, India produced 37.67 million tonnes of maize. The top maize-producing states, in order by total production are Karnataka (5.71 million tonnes), Bihar (5.63 million tonnes), Madhya Pradesh (4.34 million tonnes), Tamil Nadu (2.84 million tonnes), Telangana (2.78 million tonnes), Uttar Pradesh (2.67 million tonnes) and West Bengal (2.60 million tonnes) (7).

Crop productivity depends on favourable environmental conditions during the crop period. Climate change triggers rapid changes in weather parameters (Fig.1). Chamarajanagara district of Karnataka, characterised by limited and erratic rainfall, presents unique challenges for maize production. Although maize is photoperiod-insensitive, factors such as resource use efficiency, crop-weed competition, pest and disease incidence and uniform moisture availability are influenced by environmental conditions like rainfall, temperature, humidity, solar radiation and wind velocity. Soil moisture availability is crucial for seed germination

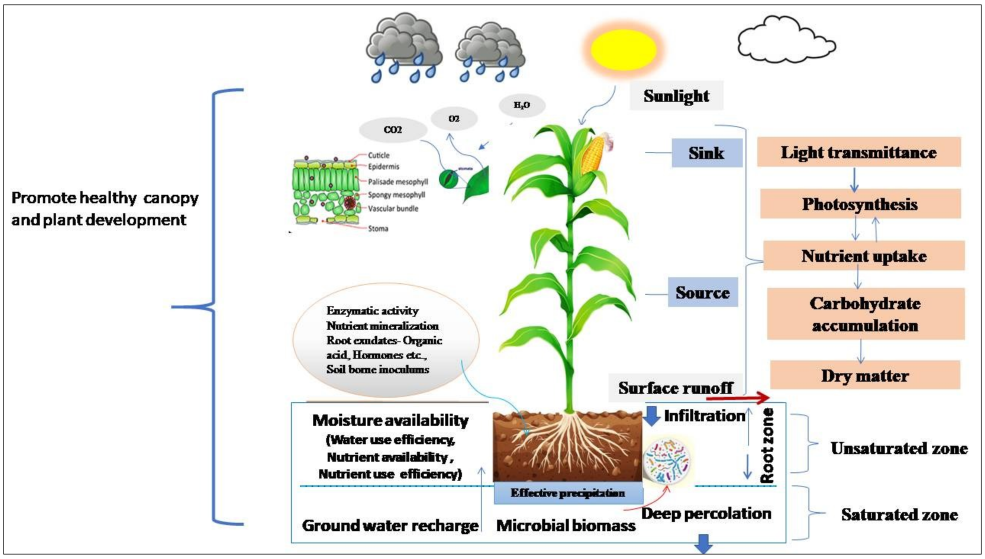


**Fig. 1.** Schematic representation of environmental factors influencing the growth and development of maize.

and population establishment under rainfed conditions, making rainfall distribution vital for crop establishment in a region.

Effective management strategies, such as optimising sowing windows are essential for effective utilisation of weather variables and maximising crop productivity in Chamarajanagara. The sowing window refers to the period during which seeds are planted, which significantly affects the growth, development and yield of maize. By selecting the appropriate sowing window, farmers can optimise water resource utilisation and enhance maize genotype performance (8). Maize, being photoperiod-insensitive, can be grown in all seasons. However, planting maize at the right time is crucial to achieving the highest possible yield of both grain and biomass (9). Farmers are concerned about how sowing date affects maize yield (10). Due to temperature variations and growing season duration, optimal maize sowing dates may vary (11). Maximum yields are often achieved when the growing season is longer and soil moisture is not a limiting factor (12). The spatial variability of rainfall differs depending on the time scale used. Geographical patterns of variability change depending on the time scale (daily, monthly, seasonal and annual) as shown by analysing rainfall during various periods. Geographical Information System (GIS) offers techniques for analysing seasonal and annual scales of rainfall variability (13).

Interpolating climate data from irregular points to regular grids covering an area of interest provides more continuous climate information. Various studies have focused on interpolating data from irregular points to regular grids using different climate variables and methods (14–18). The present study aimed to examine and quantify the spatial organisation of rainfall data at different time scales across multiple meteorological stations. Daily data covering January to December 2021 from meteorological stations in Chamarajanagara district were analysed using different interpolation techniques such as inverse distance weighted (IDW), spline, natural neighbour, trend (mathematical models), kriging and Topo to Raster (geo-statistical models) to convert point-based data into maps or grids.

Chamarajanagara has a limited number of weather stations that are not uniformly distributed to analyse rainfall data, various spatial interpolation techniques were employed (Fig. 2). Effective natural resource utilisation in the research field requires powerful tools like GIS and modelling. Spatially distributed estimates of environmental variables are increasingly necessary for use in GIS and models (19). Accurate and affordable quantitative methods for geographical data gathering and interpolation are particularly important in developing nations (20).

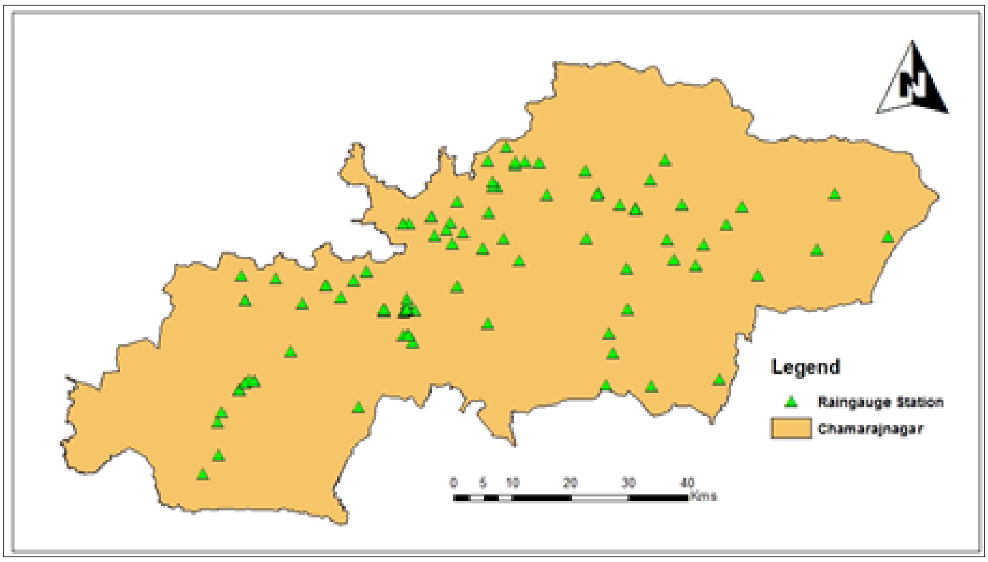


**Fig. 2.** Location of rain gauge stations in Chamarajanagara district, Karnataka, India.

Source : ArcGIS 10.8

This research study was conducted with the following objectives : Trend analysis of the meteorological data (rainfall) for various crop periods from different weather stations in Chamarajanagara district, generation of rainfall maps by using different interpolation techniques (mathematical models : IDW, spline, natural neighbor, trend; geo-statistical models-kriging, Topo to Raster) and evaluation of performance of maize genotypes under different sowing windows.

## Materials and Methods

The methodology adopted in this study is outlined in Fig. 3. To begin with, Survey of India (SOI) toposheets were used to delineate and extract the research area. Rain gauge stations were then located and ground-truthed on the toposheet to ensure spatial accuracy. Daily meteorological data, particularly rainfall, were downloaded and analysed using Microsoft Excel for preliminary data handling and trend identification. Subsequently, spatial interpolation of rainfall data was carried out on a daily basis employing various techniques, including IDW, kriging, trend, Topo to Raster and natural neighbour, to generate detailed weather maps for the study region.

The objective was to analyse daily precipitation data for different crop periods in Chamarajanagara district, which has 16 operational Hobli-level meteorological stations. These stations are shown in Fig. 4, displaying the average rainfall and the data collected through automated weather stations at Hobli headquarters over the 120-day crop growth period. Grid lines represent precipitation intervals of 0.5 mm/day. In total, rainfall data were collected from 141 meteorological stations distributed across Chamarajanagara district. These data were used for generating interpolated rainfall maps (Fig. 5–8) to capture the complete spatial variability. For station-wise comparisons and trend analysis during different crop periods, we focused on 16 operational hobli-level stations (Fig. 4A–E), as these correspond to administrative units commonly used for agricultural planning. Thus, while the interpolation analyses represent high-resolution spatial variability using all 141 points, the hobli-level station data provide a practical basis for localised agricultural interpretation. Both sets of figures are complementary, with the first providing spatial visualisation and the second offering ground-level relevance for farmers and planners.

Numerous fields of science use spatial interpolation techniques to overcome the difficulty of collecting data from multiple locations, which is often expensive and time-consuming. For the analysis of continuously changing phenomena (processes) in the real world, such as climatic variables (rainfall, temperature, humidity) and natural resource management (glaciers, wetlands, etc.), spatial analyses are becoming extremely powerful tools. Geographical Information System and modelling have therefore become necessary to estimate the spatial distribution of environmental variables. These techniques are extensively used in environmental sciences, soil science, meteorology, engineering and public health to generate information for unsampled locations.

To better understand the sources of variation and uncertainty in small-scale rainfall interpolation, rainfall data from 30 gauges in the Great Lyon area were analysed at different time steps, including annual, monthly, daily and 6-min intensities. The choice of the most suitable interpolation method depends on local rainfall characteristics, the temporal and spatial scale of analysis, the intended application of the data, the morphology of rainfall events and the structure of the rain gauge network (21).

In this study, multiple interpolation techniques were applied to generate rainfall surfaces. The IDW method estimates cell values by weighting nearby sample points inversely with distance (22). Kriging, a geostatistical approach based on regionalised variable theory, produces estimated surfaces by considering spatial autocorrelation; among its variants. Ordinary kriging was employed in this study for its computational efficiency and accuracy (23–29). The Topo to Raster method, based on an iterative finite difference technique, integrates elevation points, contours and streams to generate hydrologically correct surfaces (30–31). Natural neighbour interpolation reconstructs continuous and smooth surfaces from irregularly distributed points while preserving input values (32). Finally, the Trend surface method uses least-squares regression to fit a polynomial equation to the dataset, thereby capturing broad-scale spatial patterns (33). Together, these methods enabled a comprehensive spatial representation of rainfall variability in the study area (Fig. 9).

Study region for maize experiment: The site selection for the experiment to assess the performance of different hybrids on different dates of sowing (Table 1) was conducted at Haradanahally village, Chamarajanagara district of Karnataka (Longitude 11.89310 N, Longitude 76.95770 E, altitude 703.76 m above mean sea level) (Fig. 10). The study region falls under the southern dry zone of Karnataka and the detailed climatic parameters of the district are shown in Table 2–4 and Fig. 10. The climate is arid for most of the year except during winter, which is slightly cool. It experiences bi-modal rainfall with one peak during May–June and the other during September–October. The mean minimum temperature ranges from 14–30 °C, but occasionally touches 11 °C during December. Mean maximum temperature ranges from 27–39 °C, mostly recorded during May.

**Table 1.** Details of the treatment

| Factor A: Dates of sowing | | Factor B: Hybrids | |
|---|---|---|---|
| $D_1$ | First fortnight of June | $H_1$ | MAH14-5 |
| $D_2$ | Second fortnight of June | $H_2$ | Hema |
| $D_3$ | First fortnight of July | | |
| $D_4$ | Second fortnight of June | | |
| **Treatment combinations** | | | |
| $T_1$ | | $H_1D_1$ | |
| $T_2$ | | $H_1D_2$ | |
| $T_3$ | | $H_1D_3$ | |
| $T_4$ | | $H_1D_4$ | |
| $T_5$ | | $H_2D_1$ | |
| $T_6$ | | $H_2D_2$ | |
| $T_7$ | | $H_2D_3$ | |
| $T_8$ | | $H_2D_4$ | |

**Table 2.** Seasonal normal rainfall of the Chamarajanagara district, Karnataka

| Season | Normal Rainfall (mm) | Actual Rainfall (mm) | Deviation (%) |
|---|---|---|---|
| Winter (Jan – Feb) | 10.3 | 33.8 | 228.16 |
| Pre-Monsoon (Mar – May) | 79.1 | 70.81 | -10.48 |
| South-West Monsoon (Jun – Sept) | 320.4 | 305.6 | -4.62 |
| North-East Monsoon (Oct – Dec) | 263 | 442.2 | 68.14 |
| Total | 672.8 | 852.41 | 26.70 |

**Table 3.** Monthly climatic normal of Chamarajanagara district, Karnataka

| Months | Temperature (°C) | | Relative Humidity (%) | | Rainy Days (No.) | Wind Speed (km/hr) |
|---|---|---|---|---|---|---|
| | Max | Min | Max | Min | | |
| January | 31.82 | 11.57 | 79.03 | 31.38 | 0.32 | 4.18 |
| February | 33.93 | 12.76 | 75.45 | 29.31 | 0.16 | 5.08 |
| March | 36.07 | 15.79 | 75.07 | 24.61 | 1.58 | 4.86 |
| April | 36.73 | 19.54 | 81.89 | 33.12 | 4.89 | 4.68 |
| May | 36.68 | 19.63 | 85.81 | 43.11 | 7.68 | 6.19 |
| June | 32.80 | 19.24 | 84.48 | 52.67 | 3.21 | 7.38 |
| July | 31.78 | 19.02 | 86.23 | 56.22 | 4.89 | 8.64 |
| August | 31.79 | 18.97 | 87.27 | 54.89 | 6.05 | 8.21 |
| September | 31.96 | 18.44 | 86.10 | 53.13 | 5.53 | 7.02 |
| October | 31.41 | 17.84 | 87.71 | 54.53 | 8.21 | 4.32 |
| November | 30.44 | 16.03 | 86.22 | 55.00 | 4.42 | 3.85 |
| December | 30.65 | 12.94 | 85.34 | 45.73 | 1.42 | 4.10 |

**Table 4**. Monthly average rainfall (mm) of various rain gauge stations from January–December 2021 in Chamarajangara district, Karnataka

| | Jan-21 | Feb-21 | Mar-21 | Apr-21 | May-21 | Jun-21 | Jul-21 | Aug-21 | Sep-21 | Oct-21 | Nov-21 | Dec-21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chamarajanagara | 0.6 | 1.3 | 0.0 | 2.6 | 0.9 | 2.4 | 3.5 | 3.9 | 0.9 | 5.5 | 9.9 | 0.1 |
| Chandakavadi | 0.7 | 1.7 | 0.0 | 2.5 | 1.6 | 3.1 | 5.1 | 3.9 | 2.0 | 6.2 | 8.2 | 1.7 |
| Haradanhalli | 1.3 | 1.0 | 0.0 | 1.7 | 1.6 | 2.2 | 2.3 | 2.2 | 1.6 | 5.9 | 7.5 | 0.2 |
| Harve | 0.8 | 0.7 | 0.0 | 1.9 | 0.9 | 2.5 | 2.6 | 3.4 | 0.8 | 5.6 | 7.6 | 0.3 |
| Santemarahalli | 0.4 | 0.6 | 0.0 | 2.5 | 1.6 | 1.4 | 3.7 | 5.0 | 0.7 | 5.1 | 8.9 | 0.1 |
| Gundlupet | 2.1 | 0.8 | 0.0 | 1.9 | 0.2 | 1.1 | 1.2 | 1.9 | 0.7 | 3.2 | 3.8 | 0.7 |
| Begur | 3.5 | 0.3 | 0.0 | 3.1 | 1.6 | 1.2 | 4.3 | 1.9 | 0.6 | 6.3 | 4.6 | 1.9 |
| Terakanambi | 1.1 | 0.0 | 0.0 | 1.4 | 1.7 | 2.8 | 2.3 | 2.6 | 1.5 | 5.1 | 5.0 | 0.4 |
| Hangala | 0.4 | 0.0 | 0.0 | 1.9 | 2.1 | 1.4 | 2.3 | 2.0 | 0.9 | 6.0 | 4.5 | 1.1 |
| Kollegal | 0.1 | 0.3 | 0.1 | 1.3 | 1.2 | 1.7 | 4.2 | 2.8 | 3.2 | 7.4 | 8.5 | 0.3 |
| Hanur | 0.3 | 0.4 | 0.0 | 1.3 | 1.1 | 2.4 | 2.6 | 3.0 | 2.1 | 7.5 | 9.2 | 0.5 |
| Palya | 0.0 | 0.6 | 0.1 | 1.9 | 1.1 | 1.8 | 2.2 | 2.4 | 1.0 | 8.0 | 7.5 | 1.6 |
| Ramapura | 0.1 | 0.1 | 0.0 | 3.2 | 1.5 | 1.2 | 3.5 | 3.6 | 3.0 | 7.7 | 7.7 | 0.5 |
| Yelandur | 0.2 | 0.3 | 0.0 | 2.4 | 0.9 | 1.9 | 3.7 | 3.8 | 0.8 | 7.1 | 8.4 | 0.1 |
| Agara | 0.4 | 0.9 | 0.0 | 2.9 | 0.9 | 0.9 | 3.2 | 3.0 | 3.1 | 8.2 | 10.9 | 0.2 |
| Lokanahallli | 0.1 | 0.4 | 0.0 | 1.2 | 1.6 | 2.4 | 2.6 | 1.8 | 1.7 | 5.4 | 6.2 | 0.9 |

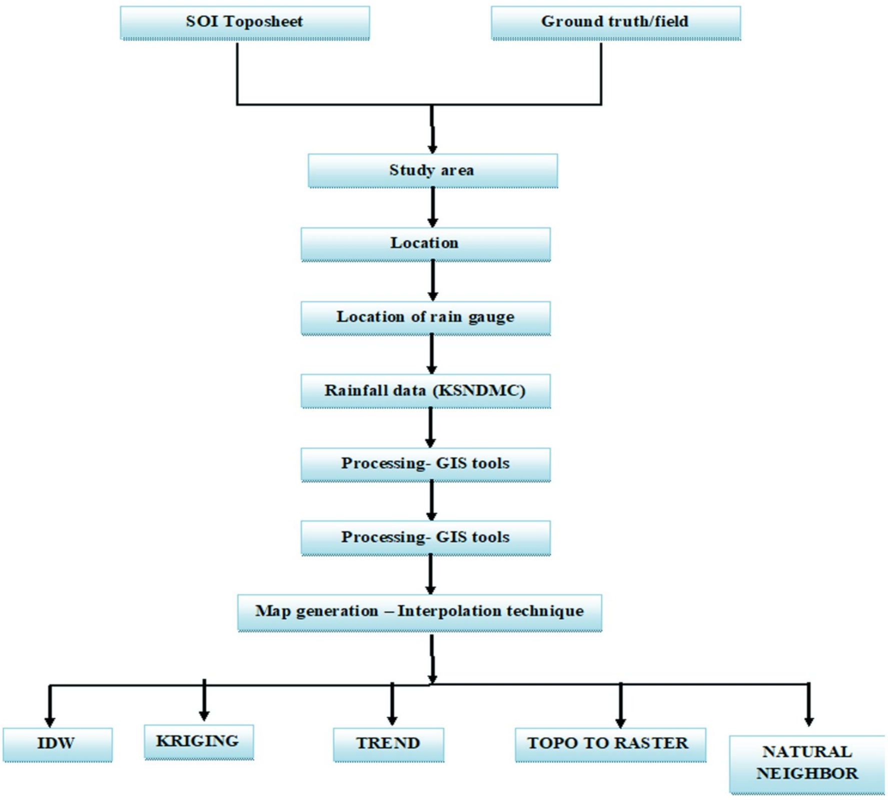


**Fig. 3**. Flowchart of the adopted methodology.

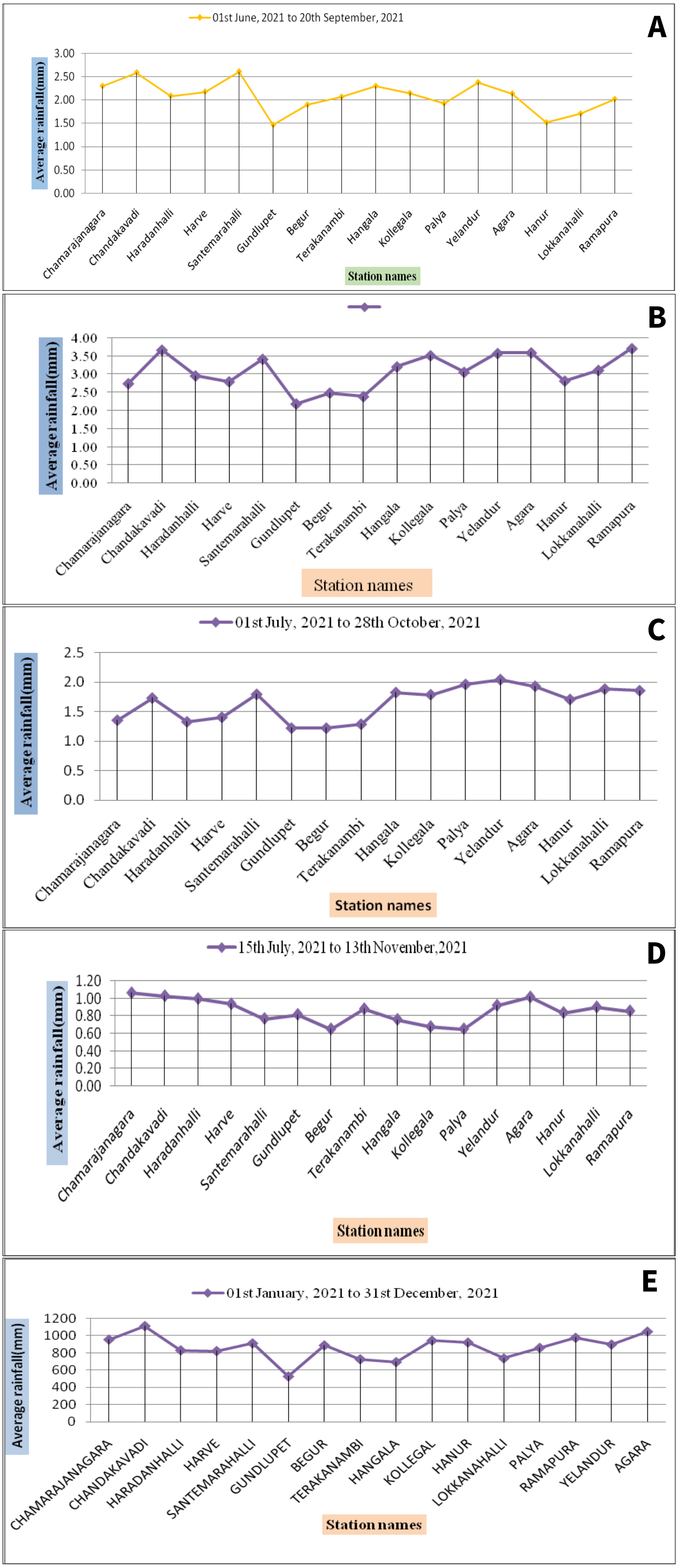


**Fig. 4.** Hobliwise average precipitation during crop period from: A. 1st June, 2021 to 20th September, 2021, B. 15st June, 2021 to 03rd October, 2021, C. 01st July, 2021 to 28th October, 2021, D. 15th July, 2021 to 13th November, 2021, E. Annual spatial distribution of rainfall across 16 hobli stations in Chamarajanagara district during 2021.

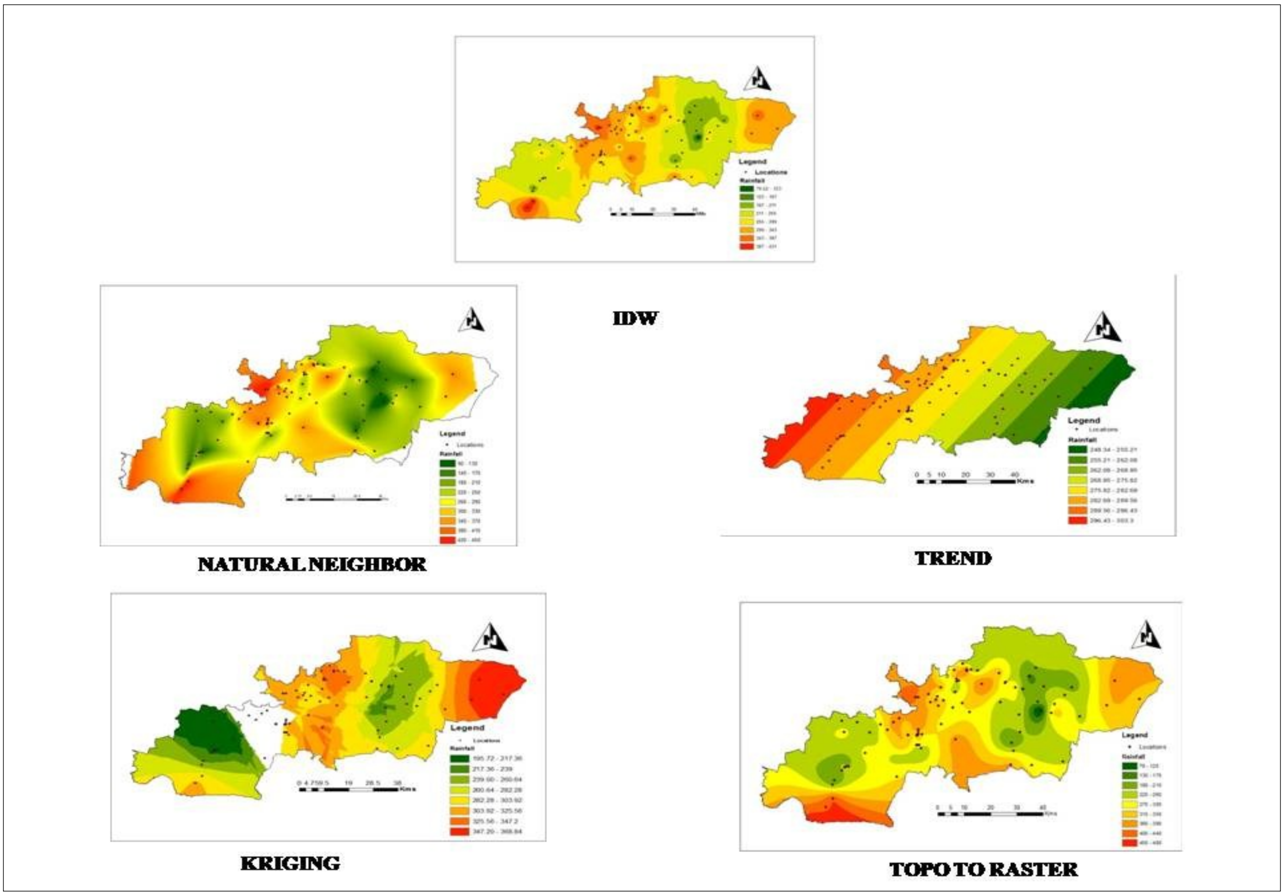


**Fig. 5.** June first fortnight interpolation technquie for various rain guage station of chamarajanagara district, Karnataka.
Source : ArcGIS 10.8

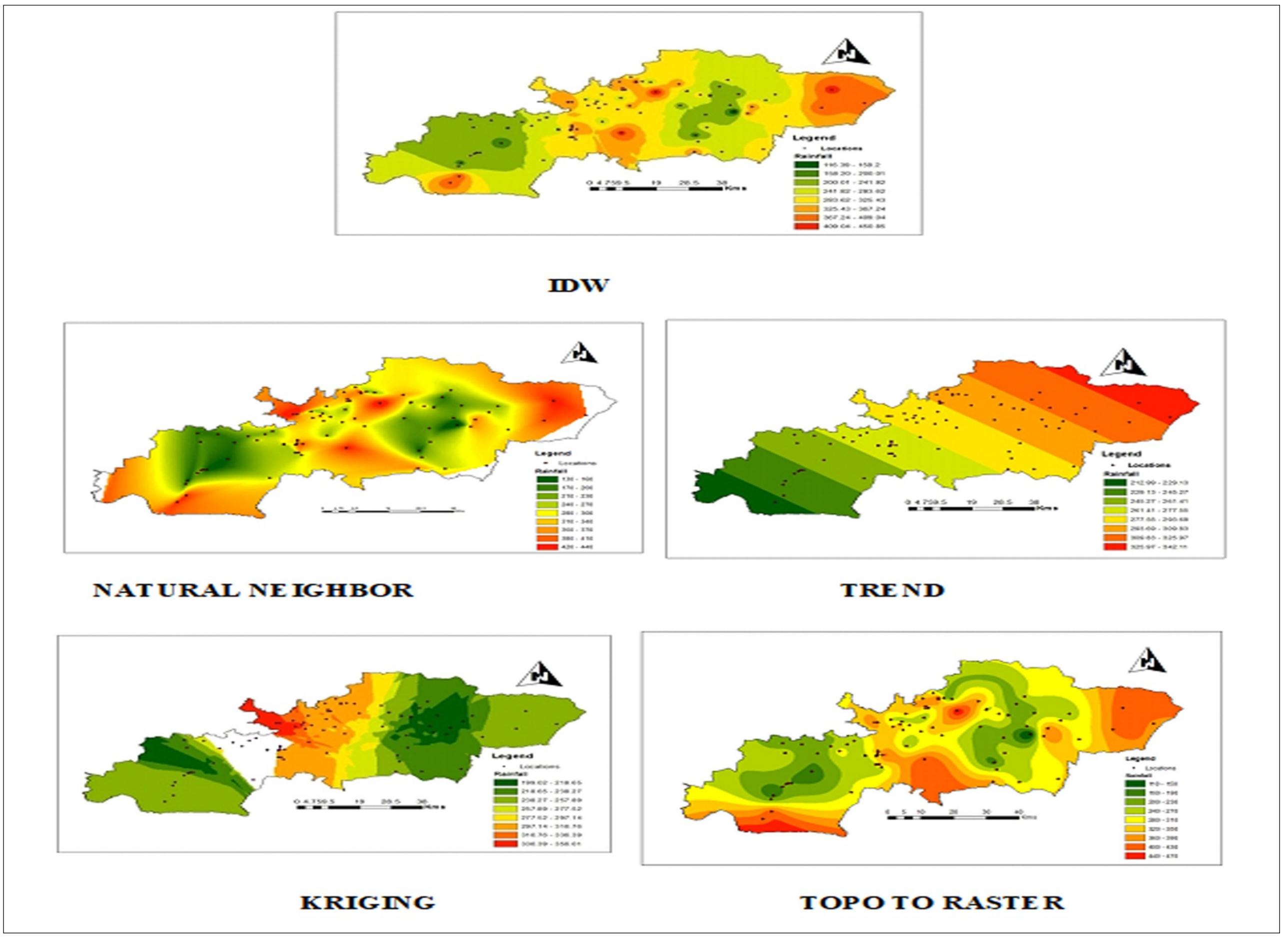


**Fig. 6.** June second fornight interpolation technquie for various rain guage station of Chamarajanagara district, Karnataka.
Source : ArcGIS 10.8

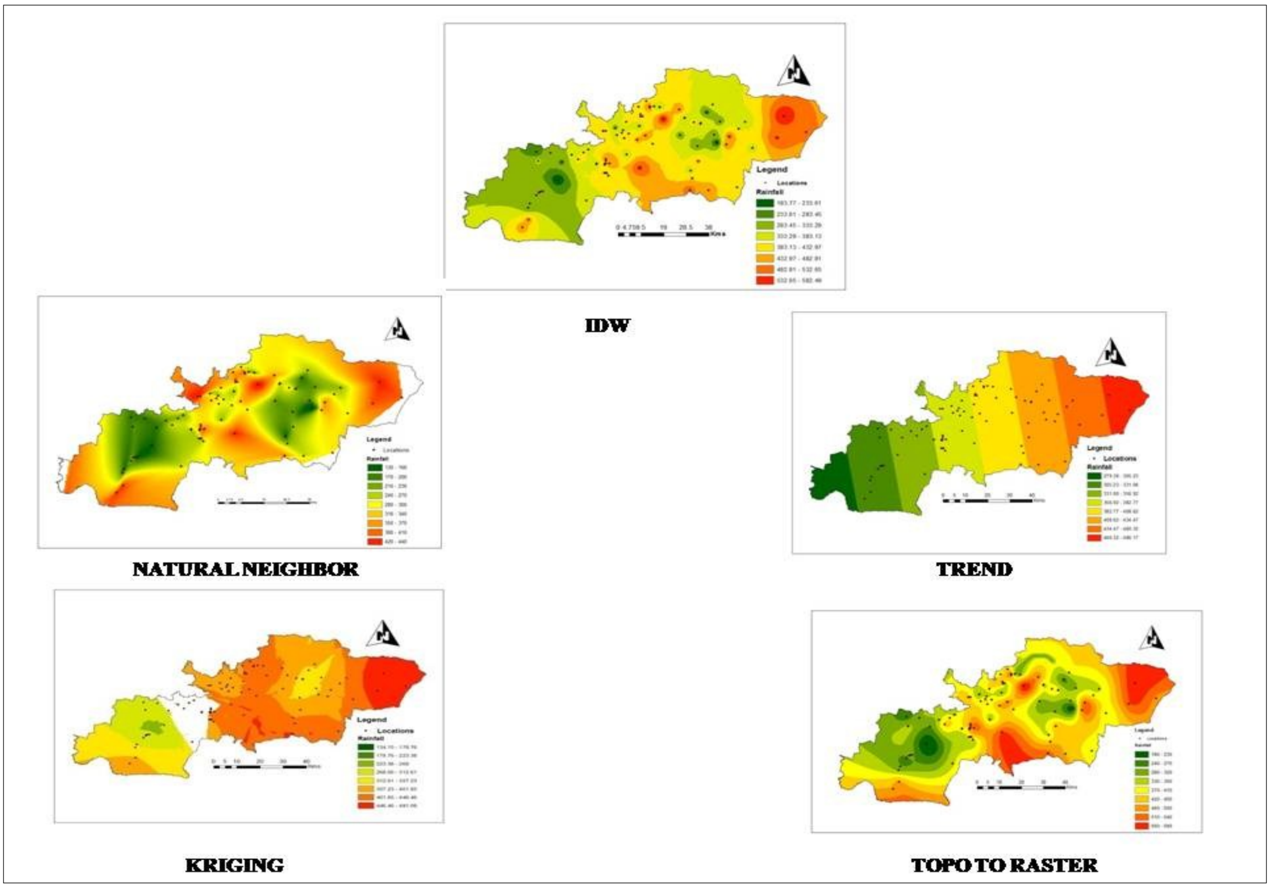


**Fig. 7.** July first fortnight interpolation technique for various rain gauge stations of Chamarajanagara district, Karnataka.
Source : ArcGIS 10.8

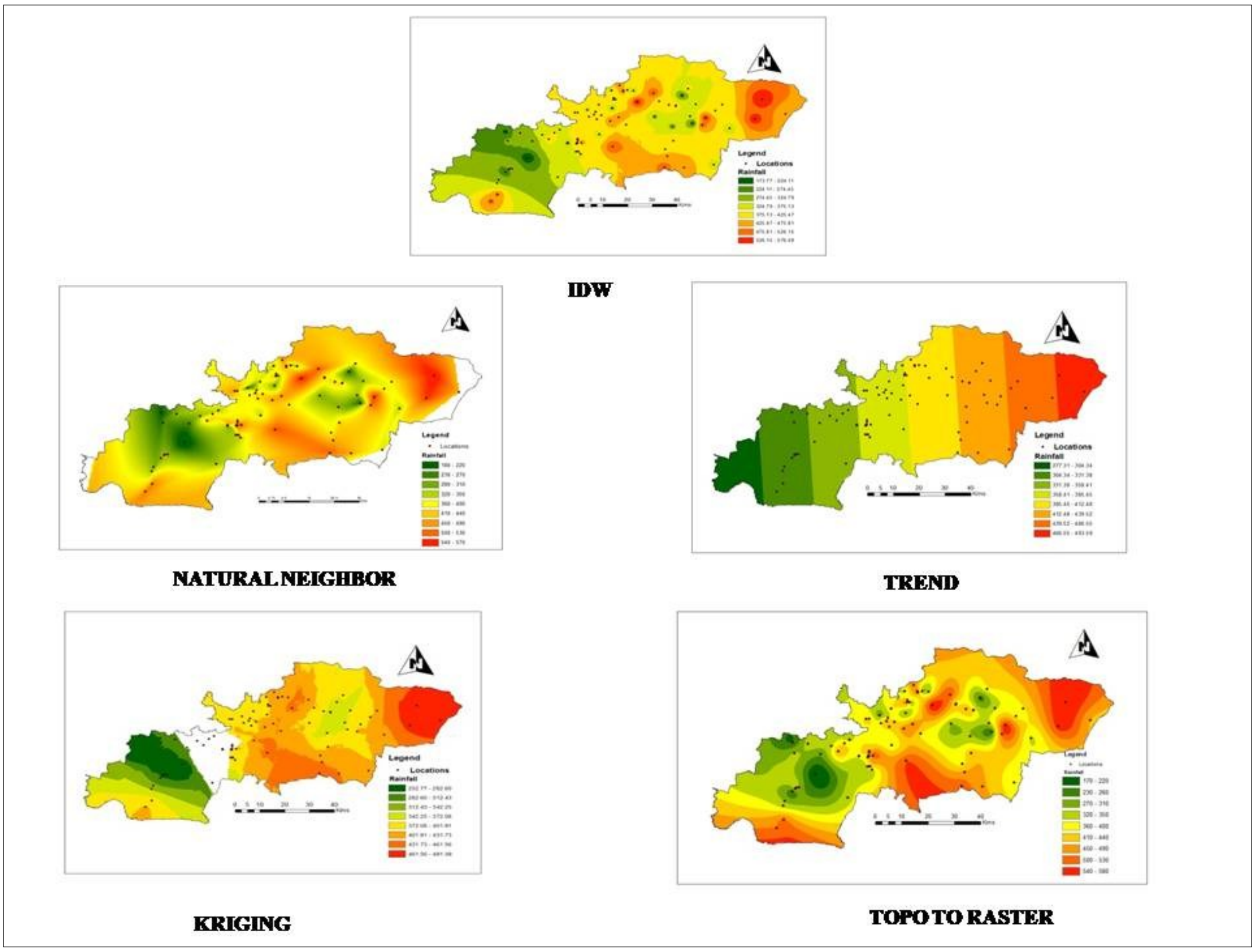


**Fig. 8.** July second fortnight interpolation technique for various rain gauge stations of Chamarajanagara district, Karnataka.
Source : ArcGIS 10.8

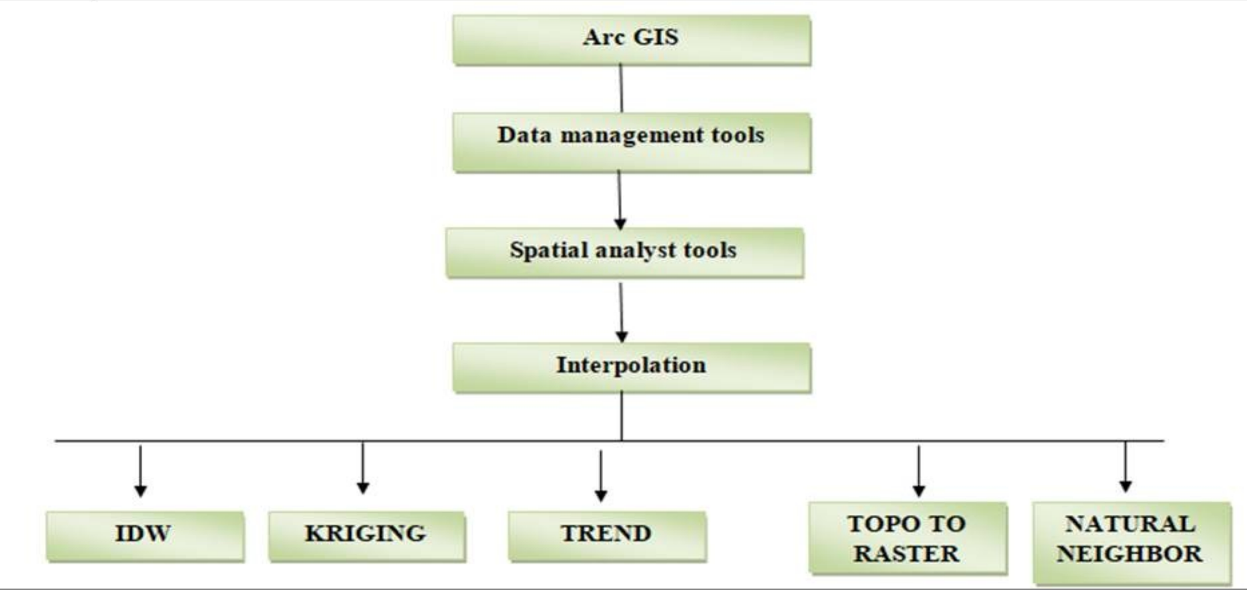


**Fig. 9.** Flowchart of map generations.

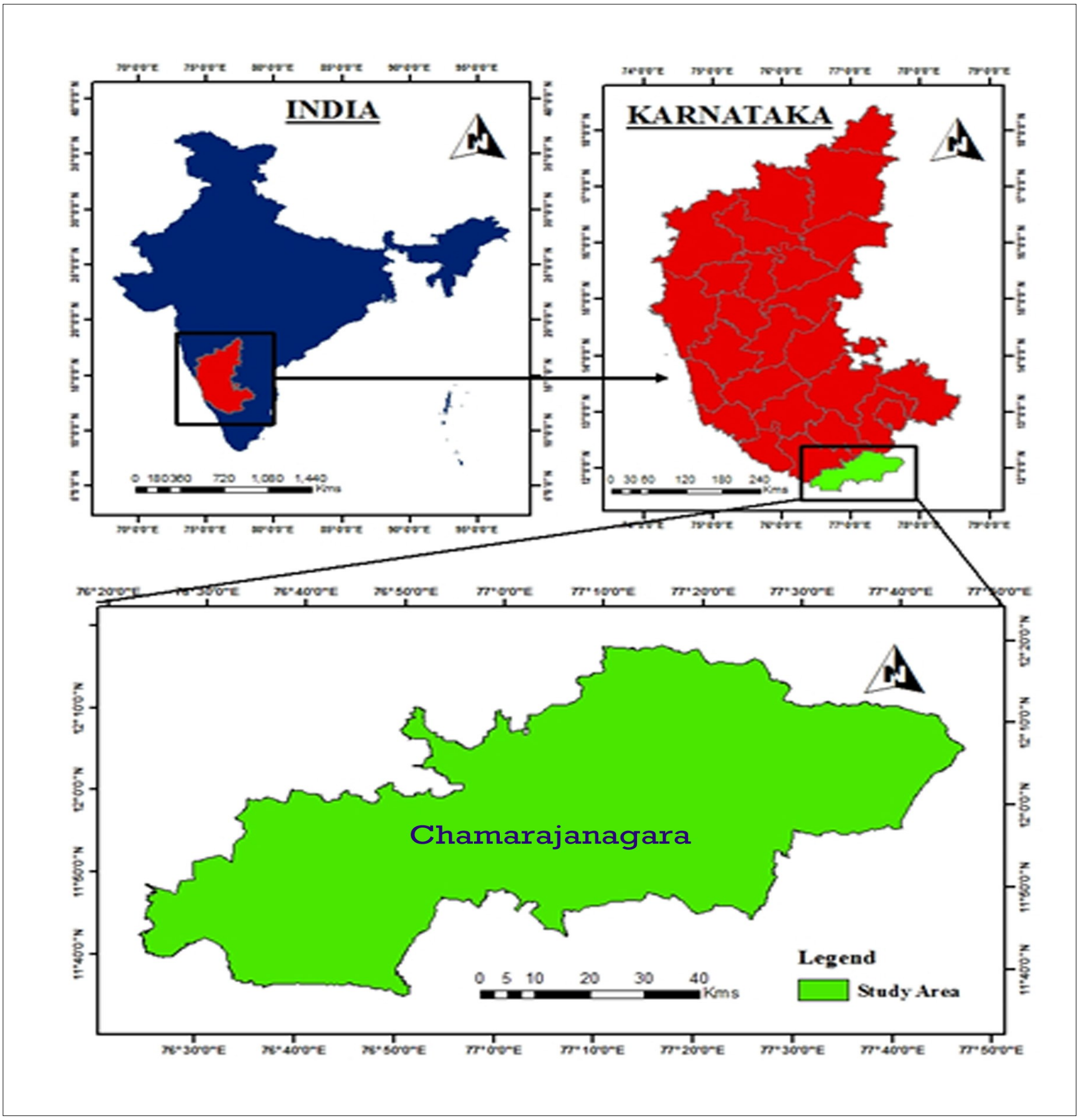


**Fig. 10.** Details of the study area at Chamarajanagara district, Karnataka.

Source : ArcGIS 10.8

The daily weather data (temperature, humidity, etc.) were collected from an automated weather station located at the Indian Council of Agricultural Research (ICAR) – Krishi Vigyan Kendra, Haradanahally farm, 1.5 km from the experiment site (Fig. 10). Rainfall data, however, were obtained from multiple meteorological stations across Chamarajanagara district (141 stations in total) to capture spatial variability. For crop data analysis, only the experimental site was used, whereas hobli-level station data (16 points) were used for comparison across sowing windows. This distinction between datasets has been made to ensure both district-level spatial representation and site-specific experimental relevance.

## Results and Discussion

### Trend analysis of the meteorological data (rainfall) for various crop periods from different weather stations in Chamarajanagara district

From June 1–September 20, 2021 Gundulpete station recorded the least precipitation (1.47 mm) while Santemarahalli station recorded the most (2.61 mm). During the crop season from June 15–October 3, 2021 Gundulpete station recorded the lowest average precipitation (2.17 mm), whereas Chandakavadi station recorded the highest (3.66 mm). From July 1–October 28, 2021 Gundulpete station again recorded the lowest average rainfall (1.22 mm), while Yelandur station recorded the highest (2.04 mm). The overall district average precipitation during this period was 3.1 ± 0.4 mm/day (mean ± SE). Between July 15, 2021 and November 11, 2021, Chamarajanagara station recorded the highest average rainfall (1.07 mm) and Begur station the lowest (0.65 mm).

For the entire year from January 1–December 31, 2021, Gundulpete recorded the lowest average annual rainfall (529.5mm) while Chandakavadi recorded the highest (1115mm). This study used daily, monthly and annual rainfall data and the differences in the time steps used for interpolation might explain the variation in results compared to studies, which also used daily, monthly and annual time steps, respectively (15, 17). The mean annual rainfall across the district was 850 ± 75 mm (mean ± SE), with significant spatial heterogeneity (CV = 23 %). Grid lines on the Y-axis represent intervals of 200 mm rainfall. The observed rainfall pattern indicates a north-south gradient in precipitation distribution, with northern hoblis receiving comparatively higher rainfall than southern hoblis.

October and November 2021 had the highest number of rainy days, followed by July 2021. In contrast, March 2021 had the fewest wet days, followed by January and February (Table 1). In the visualisation, bold red indicates lower average precipitation of less than 1 mm, while bold black represents the highest average precipitation among the 141 meteorological stations every month. Although our study area has a sufficient number of samples, they are not evenly distributed. The primary objective was to examine daily rainfall across several locations within the study area (33) (Table 2-4).

### Generation and comparison of weather (rainfall) maps by using different interpolation techniques

Weather (rainfall) maps were generated and compared using five interpolation techniques: IDW, trend analysis, natural neighbour interpolation, Topo to Raster and kriging. Each technique exhibits distinct advantages and limitations for spatial rainfall analysis. The appropriateness of each method is influenced by factors such as the spatial distribution of rainfall data, terrain characteristics, the availability of sample points and the required level of accuracy. The map outlines the Chamarajanagara region and uses a colour gradient from green to red to represent varying rainfall levels. A legend positioned on the right side of the map provides the corresponding rainfall values (in mm) for each colour category. Areas shaded green correspond to lower rainfall amounts, while yellow and red areas indicate higher rainfall intensities. Small black dots scattered throughout the map likely denote the locations of meteorological stations. Four distinct rainfall periods relevant to maize cultivation were analysed: the first and second fortnights of June and the first and second fortnights of July, encompassing a total duration of 120 days (Fig. 5).

In the IDW analysis, the highest rainfall is concentrated in the southwestern and northeastern parts of the district, while the central region receives the least rainfall. The Natural neighbour method shows a similar pattern, with the southwestern and northeastern corners experiencing more rainfall, but with smoother transitions between different rainfall zones. Trend interpolation reveals a gradual change in rainfall from southwest to northeast, with the highest amounts occurring in the southern corner of the region. Kriging interpolation presents a more complex pattern, featuring numerous separate pockets of high rainfall dispersed throughout the area. The Topo to Raster interpolation approach also displays smoother transitions between rainfall zones, similar to the natural neighbour method, but with a slightly different distribution pattern. For the first fortnight of June, both natural neighbour interpolation and trend analysis indicate that areas near Hanur and Kollegal receive sufficient rainfall and are suitable for growing maize. However, locations near Gundlupete receive less rainfall and are less suitable. Although the Yelandur area receives moderate rainfall, its suitability for growing maize is influenced by nearby rainfall patterns (Fig. 6).

In the above maps, areas with higher rainfall amounts are shown by the warmer colours (yellow, orange and red), which are focused on the northern and eastern parts of the district. Areas with lower rainfall amounts are represented by the cooler colours (green), primarily located in the central and southern parts of the district. The spatial distribution of rainfall exhibits a relatively uniform pattern with gradual transitions between regions of varying precipitation levels. Rainfall seasonality is an important factor influencing agricultural productivity (34). Previous studies have indicated that spring and summer are the main rainfall seasons in the region . Furthermore, topography plays a significant role in determining the spatial variability of rainfall (35). The rainfall patterns described in these sources indicate that the regional variations in monsoon precipitation over India are quite significant, with substantial differences in rainfall amounts even over relatively short distances (35, 36). This highlights the importance of analysing rainfall trends at finer spatial scales rather than just looking at all-India averages (37). Previous research has found that changes in the spatial and temporal distribution of rainfall can impact factors like runoff, soil moisture and groundwater storage, thereby influencing the frequency of droughts and floods (38, 39). Examining the spatial variability of rainfall is crucial for understanding its impacts on various environmental processes in India (40) (Fig. 7).

A comprehensive analysis of the rainfall distribution patterns, specifically focusing on IDW, which displays a distinct and uneven pattern of rainfall distribution. The district experiences concentrated pockets of high rainfall amounts, primarily in the central and southwestern parts. There are patches of lower rainfall amounts (yellow and green) scattered throughout the district. The Natural neighbour interpolation method results in a more polished representation of rainfall distribution when compared to IDW. The most significant rainfall amounts (orange and red) are more widespread, covering a larger area in central and southwestern regions. The rainfall amounts in the northern and eastern parts of the district are comparatively lower. The Trend interpolation method produces a smoother and more gradual transition between regions with varying levels of rainfall. District experiences varying levels of rainfall, with the highest amounts found in the northeast corner. As you move towards the southwestern part, the rainfall gradually decreases.

The Kriging interpolation method creates a visually pleasing surface representation of the rainfall distribution. The district experiences varying levels of rainfall across its different regions. The central and southern parts receive the highest amounts, indicated by the colours red and orange. In contrast, northern and eastern regions receive relatively lower amounts of rainfall, shown by the colour green. The Topo-to-Raster method, which incorporates topographic information, reveals a rainfall distribution pattern that is more irregular and localised. The district experiences varying levels of rainfall across different regions. The central, southwestern and northeast parts of the district receive the highest amounts of rainfall, indicated by red and orange colours on the map. In contrast, the northern and eastern regions receive relatively lower amounts of rainfall, as shown by green and yellow colours.

From the rainfall distribution patterns depicted in the five images, it is revealed that the southwestern and central portions of Chamarajanagara district receive a moderately lower amount of precipitation (as represented by the cooler green and yellow colours). The northern and eastern regions received a greater amount of precipitation (as indicated by the warmer orange and red colours). The majority of the district's lands, except for a few locations in the central region, are appropriate for maize production during the second fortnight of June, according to the findings of kriging research. Different interpolation methods, such as natural neighbour, trend analysis, IDW and Topo-to-Raster, exhibit comparable patterns, which suggest that the regions surrounding Hanur, Kollegal and Yelandur are suitable for growing maize, whereas the regions surrounding Gundlupete are less suitable (41). In mid-June, the northern, eastern and portions of central regions have greater rainfall, making them better suited for maize production. In contrast, the southwestern region and portions of central Chamarajanagara see drier weather, making them less fit for maize cultivation (42). In IDW, there is a noticeable difference in rainfall levels between eastern and central regions, which receive higher amounts of rainfall and the western areas, which experience lower amounts. The natural neighbour showcases a balanced distribution of rainfall levels ranging from moderate to high across the majority of the regions. There are a few localised areas with lower rainfall and a handful of pockets experiencing exceptionally high rainfall. The trend interpolation reveals a clear division between east and west, with western regions having less rainfall (green shades) and the eastern regions receiving greater amounts (yellow to red shades).

Mapping is a more intricate pattern, showcasing numerous pockets of different rainfall intensities throughout the region. The central and eastern regions experience higher levels of rainfall, indicated by yellow to red colours, while the western regions receive comparatively lower amounts, represented by green shades. These variations in rainfall distribution may be attributed to factors like shifts in weather patterns, seasonal impacts, topographical influences or the representation of various climate scenarios (43, 44). July first fortnight and second fortnight results show that trend analysis identifies July as the best time for maize cultivation in the lower part of the study area based on rainfall patterns. It suggests that there is a consistent and favourable trend in rainfall during this period. Trend analysis may reveal a consistent increase in rainfall during July compared to other months or fortnights. This could indicate a pattern of increasing precipitation over time, which is beneficial for maize growth and yields during the critical stages of the crop (45). Significant insights can be gathered through analysis of long-term rainfall data to determine the optimal planting period for maize in the region (Fig. 8).

The maps utilise a colour scale to depict various levels of rainfall with colours smoothly transitioning from green (indicating lower rainfall) to yellow, orange and red (indicating higher rainfall). There is a noticeable difference in rainfall distribution across the region, with higher amounts of rainfall observed in eastern and southeastern parts. In contrast, the western and northern areas experience lower levels of rainfall. In Natural neighbour, there seems to be a slight expansion of the high rainfall zone (orange and red) towards the central and northern areas when compared to IDW. The Trend shows a noticeable change in the high rainfall zone (orange and red) moving towards central and northern regions (46). This suggests that there has been an increase in rainfall amounts in those areas compared to the IDW and Natural neighbour methods. It appears that in kriging, there has been a slight contraction in the high rainfall zone (orange and red) with more areas now experiencing moderate to low rainfall levels (yellow and green colours) (47, 48). The Topo to Raster tool reveals a rainfall pattern that closely resembles kriging. The areas with high rainfall (indicated by orange and red colours) are concentrated in eastern and central regions, while western and northern parts receive comparatively lower amounts of rainfall (represented by green colours) (49).

The maps offer a visually appealing way to showcase the spatial distribution of rainfall, making them valuable for activities such as agriculture, water resource management and weather forecasting (50, 51). Overall, the results suggest that June may offer suitable conditions for maize cultivation in upper regions like Hanur and Kollegal and July stands out as the most advantageous period in lower regions such as Gundlupet and surrounding areas. Understanding these spatial and temporal variations in rainfall patterns is essential for maximising agricultural productivity and ensuring sustainable crop management practices (52). Rainfall patterns in the region exhibit distinct spatial and temporal variations, which have significant implications for agricultural planning and water resource management (53).

A limitation of this study is that, although rainfall data were interpolated from multiple meteorological stations, crop performance data and other weather variables were collected from a single location. While this provides useful insights into how rainfall variability influences maize performance, multi-location crop trials combined with site-specific weather observations would further strengthen the correlations. Future studies should incorporate multi-site experimentation to validate and expand upon these findings. Study emphasises the importance of timing in agricultural practices, whether it is selecting the optimal sowing date or determining the most favourable period for cultivation based on rainfall patterns. While the rainfall analysis provides insights into seasonal trends and spatial variability, the sowing date study focuses on the direct impact of timing on crop yield and quality (Fig. 11-15).

The recommendation to sow maize during the first week of July is the most favourable period for cultivation in lower regions, suggesting a synergy between optimal timing and favourable climatic conditions. Together, these findings underscore the significance of informed decision-making in agricultural planning, considering both climatic factors and agronomic practices to maximise crop productivity and quality (Table 5).

### Ordinary kriging - Gaussian

In this study, we used spatial interpolation techniques such as IDW and ordinary kriging, simple kriging and universal kriging to examine daily meteorological (rainfall) data for 2021. To determine the degree of stability that exists between different kriging models (ordinary, simple and universal) and various variogram models (circular, stable and Gaussian) is investigated. There was a reduced stable error and it implies that the stable and Gaussian distributions exhibit less variability or fluctuations in comparison to circular distribution (Table 5). This may imply that the stability of distribution exhibits a behaviour that is more consistent or predictable within its range when compared to the behaviour of other distributions.

### Ordinary kriging

The Gaussian and stable variogram models exhibited comparable performance, with the lowest root mean square error (RMSE) of 120.1836 and root mean square standardised error (RMSSE) of 1.035165, suggesting superior accuracy compared to the Circular variogram model. The average standard error (ASE) values for both the Gaussian and stable models were similar, with a value of 115.2187, indicating that the uncertainty estimates were comparable.

### Simple kriging

The Gaussian and stable variogram models exhibited comparable performance, albeit with marginally lower RMSE (119.2497) and RMSSE (1.04516) values in comparison to the circular variogram model. The ASE values for the Gaussian and stable models (114.1515) were lower than those for the circular model (114.5183), suggesting slightly reduced uncertainty estimates. In general, the simple kriging model using Gaussian or stable variograms showed superior performance compared to the circular variogram model (Table 6).

**Table 5.** Total number of rainy days of the rain gauge station on a monthly basis from January to December 2021 in Chamarajangara district, Karnataka

| | Jan-21 | Feb-21 | Mar-21 | Apr-21 | May-21 | Jun-21 | Jul-21 | Aug-21 | Sep-21 | Oct-21 | Nov-21 | Dec-21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chamarajanagara | 2 | 2 | 0 | 5 | 5 | 3 | 10 | 8 | 4 | 12 | 13 | 1 |
| Chandakavadi | 2 | 2 | 0 | 5 | 4 | 6 | 7 | 7 | 2 | 14 | 12 | 1 |
| Haradanhalli | 3 | 2 | 0 | 4 | 5 | 7 | 7 | 6 | 4 | 11 | 11 | 1 |
| Harve | 2 | 2 | 0 | 7 | 3 | 5 | 10 | 6 | 3 | 8 | 12 | 2 |
| Santemaralli | 2 | 2 | 0 | 5 | 7 | 2 | 8 | 13 | 2 | 12 | 9 | 0 |
| Gundlupet | 1 | 1 | 0 | 5 | 1 | 5 | 7 | 9 | 3 | 9 | 9 | 2 |
| Begur | 1 | 1 | 0 | 7 | 5 | 6 | 13 | 6 | 1 | 11 | 11 | 3 |
| Terakanambi | 2 | 0 | 0 | 4 | 6 | 8 | 10 | 12 | 4 | 9 | 15 | 2 |
| Hangala | 1 | 0 | 0 | 7 | 8 | 7 | 10 | 8 | 5 | 9 | 11 | 2 |
| Kollegal | 0 | 2 | 1 | 4 | 4 | 6 | 8 | 9 | 4 | 14 | 12 | 1 |
| Hanur | 1 | 2 | 0 | 5 | 4 | 6 | 7 | 8 | 6 | 12 | 12 | 1 |
| Lokkanahalli | 1 | 2 | 0 | 5 | 5 | 6 | 8 | 8 | 4 | 13 | 13 | 1 |
| Palya | 0 | 1 | 1 | 6 | 4 | 5 | 7 | 8 | 5 | 14 | 10 | 2 |
| Ramapura | 0 | 0 | 0 | 5 | 3 | 3 | 9 | 6 | 5 | 13 | 9 | 2 |
| Yelandur | 1 | 2 | 0 | 6 | 3 | 4 | 8 | 11 | 2 | 13 | 11 | 0 |
| Agara | 2 | 2 | 0 | 6 | 3 | 5 | 6 | 9 | 7 | 13 | 13 | 0 |

**Table 6.** Cross-validation comparison for interpolation models

| Period | Statistical criteria | Model - Ordinary krigging | | |
|---|---|---|---|---|
| | | Circular | Gaussian | Stable |
| Annual | RMSE | 121.8322 | 120.1836 | 120.1836 |
| | RMSSE | 1.04773 | 1.035165 | 1.035165 |
| | ASE | 115.2283 | 115.2187 | 115.2187 |
| | | Model - Simple krigging | | |
| | | Circular | Gaussian | Stable |
| Annual | RMSE | 120.4439 | 119.2497 | 119.2497 |
| | RMSSE | 1.0468 | 1.04516 | 1.040516 |
| | ASE | 114.5183 | 114.1515 | 114.1515 |
| | | Model - Universal krigging | | |
| | | Circular | Gaussian | Stable |
| Annual | RMSE | 121.8332 | 120.1836 | 120.1836 |
| | RMSSE | 1.04773 | 1.035165 | 1.035165 |
| | ASE | 115.2283 | 115.2187 | 115.2187 |

RMSE: Root-mean-square, RMSSE: Root-mean-square standardised, ASE:Average standard error.

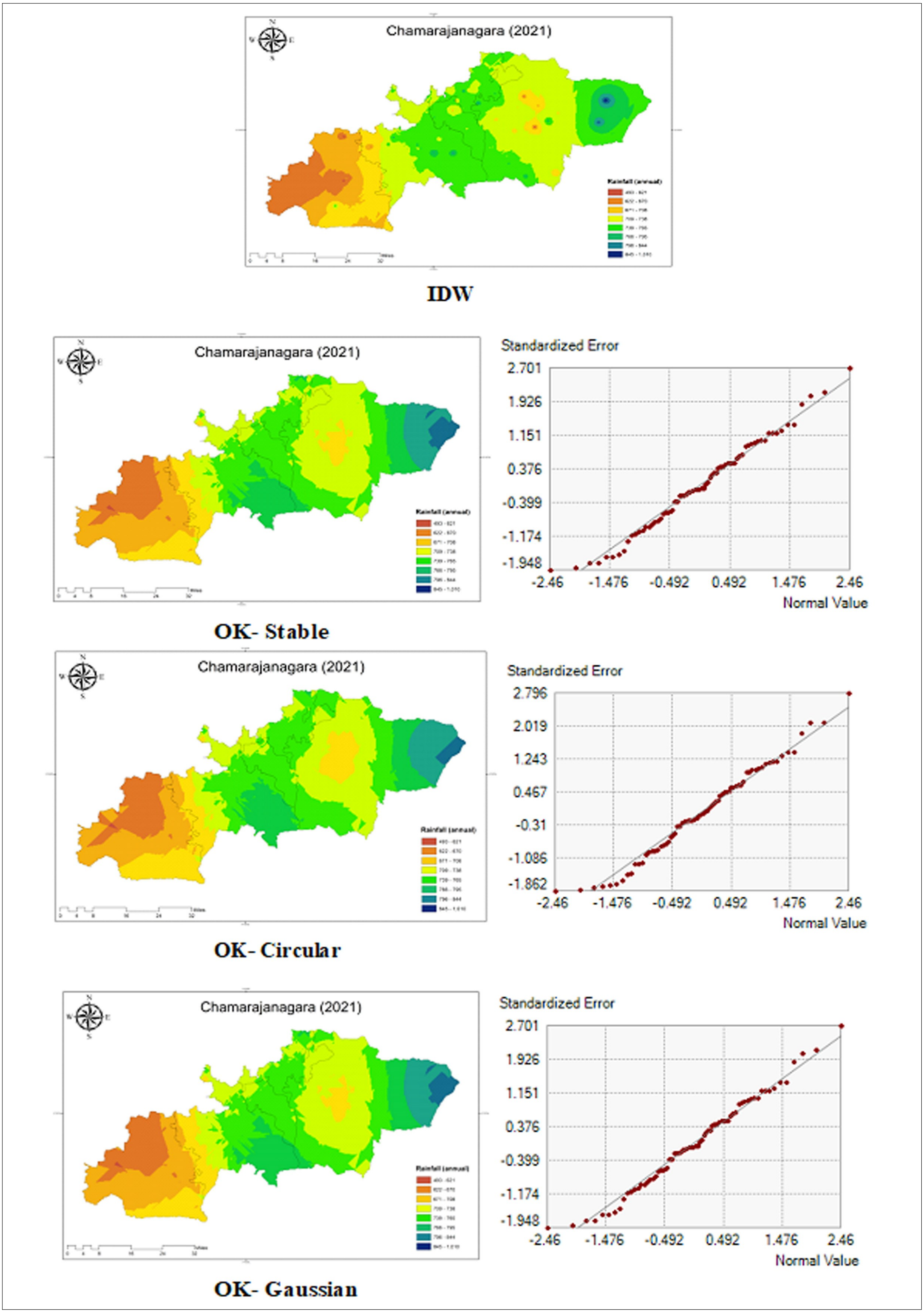


**Fig. 11.** Yearly interpolation technique for various rain gauge stations of Chamarajanagara district of Karnataka.

Source : ArcGIS 10.8


**Fig. 12.** Influence of sowing windows on plant height at different growth intervals of 30, 60, 90 and at harvest in Maize under different treatments.

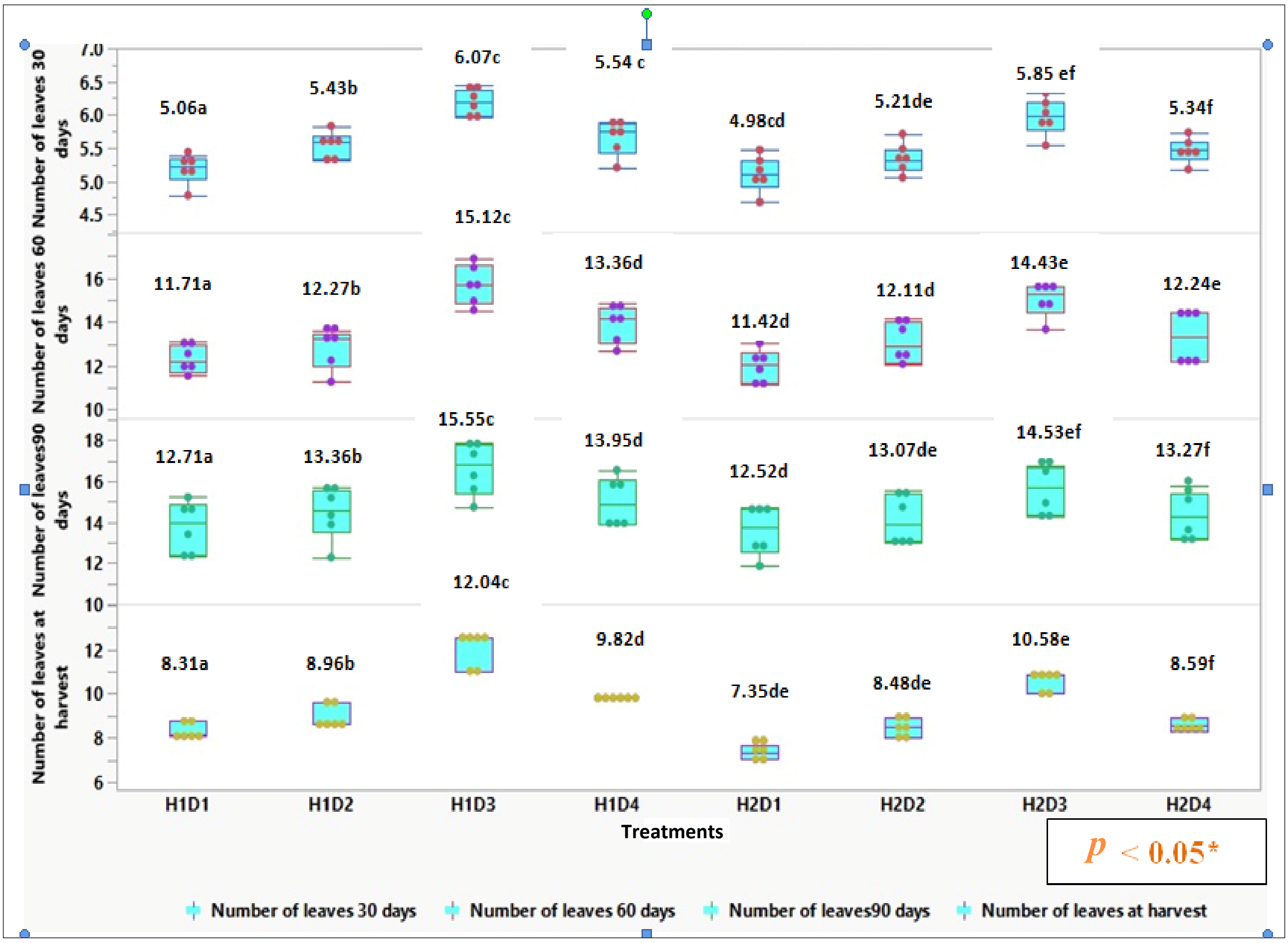


**Fig. 13.** Influence of sowing windows on the number of leaves per plant at different growth intervals, 30, 60, 90 and at harvest in Maize under different treatments.

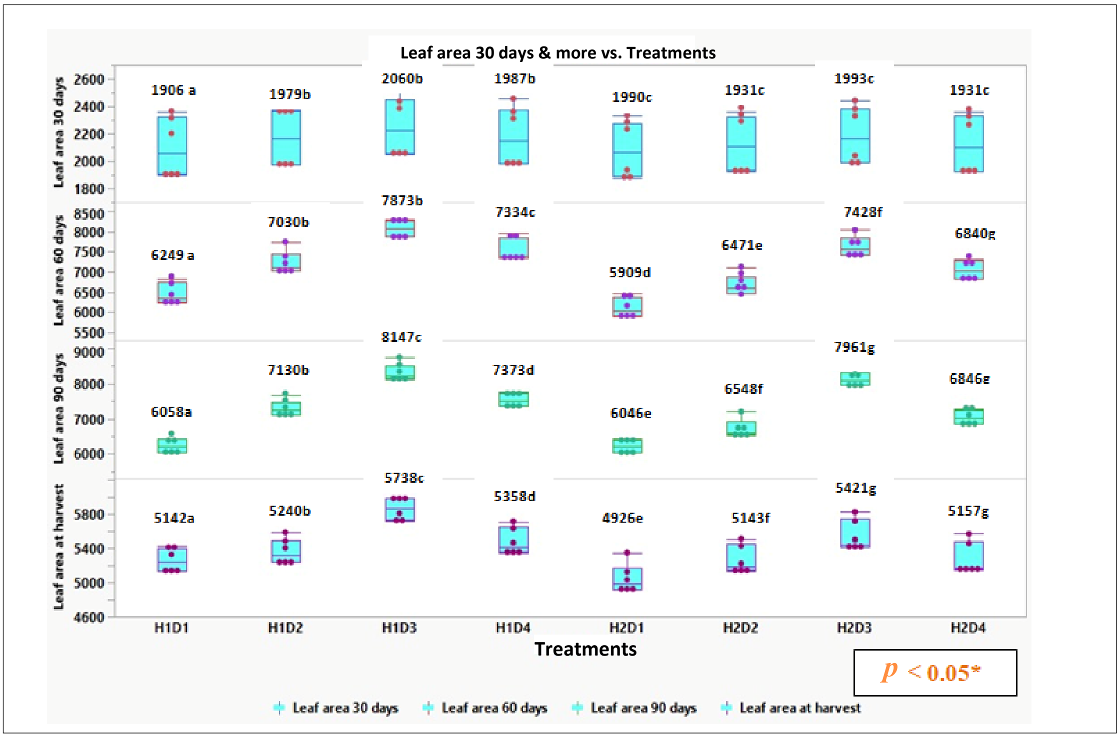


**Fig. 14.** Influence of sowing windows on leaf area at different growth intervals 30, 60, 90 and at harvest in maize under different treatments.

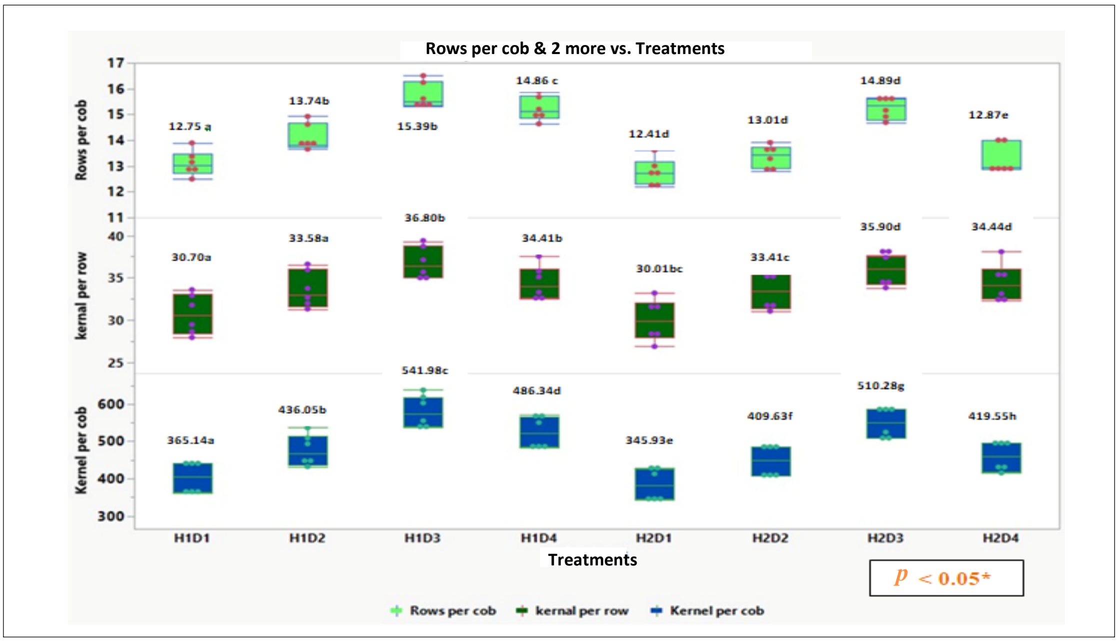


**Fig. 15.** Influence of sowing windows on kernel per cob, kernel per row, rows per cob at different growth intervals, 30, 60, 90 and at harvest in maize under different treatments.

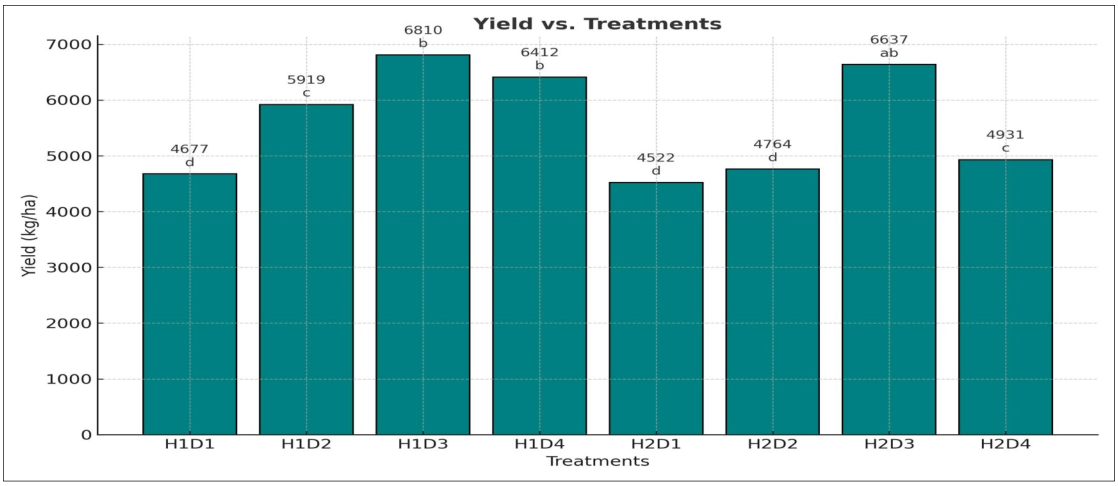


**Fig. 16.** Grain yield of maize hybrids under in maize under different treatments.

### Universal kriging

There was no difference in performance between the Gaussian and stable variogram models, with the RMSE being 120.1836, the RMSSE being 1.035165 and the ASE being 115.2187 overall. The performance of universal kriging with Gaussian and stable variograms was comparable to that of ordinary kriging while using the same variogram models. The Gaussian and stable variogram models fared better for ordinary and universal kriging than the circular variogram model, showing lower RMSE, RMSSE and ASE values. With somewhat lower RMSE, RMSSE and ASE values, the Gaussian and stable variogram models outperformed the circular variogram model for simple kriging as well. With the lowest RMSE and RMSSE values when compared to the other model-variogram combinations, the simple kriging model with gaussian or stable variograms seems to offer the greatest performance overall.

Based on the study of rainfall data and the creation of several maps, it has been proven that the greatest amount of rainfall (709-1010) took place in the eastern section of the district, particularly in the Kollegala block. In contrast, the western section of the district, particularly Gundulpete and Chamarajanagara block, as well as Yelanduru block, experienced the least amount of rainfall. The rainfall ranges in these areas were 671–765 mm and 739–765 mm, respectively. Protective irrigation must be ensured with respect to rainfed maize crop selection in order to produce a sustainable yield. The annual rainfall distribution in Gundulpete is characterised by a rather narrow range, varying between 490 and 700 mm.

### Evaluation of the performance of maize genotypes under different sowing windows

Different sowing windows significantly influenced maize growth and yield performance (54). The observed variations in plant height, leaf number and leaf area between early (June) and optimal (July) sowings highlight the importance of aligning genotype growth cycles with favourable environmental conditions. The superior performance of MAH 14-5 in July first fortnight (H1D3) confirms that genotype × environment interactions strongly determine crop vigour and yield expression (55). These results support the notion that identifying the optimum sowing window is essential for maximising both growth parameters and final productivity.

### Impact of sowing window on growth parameters of maize

Plant height in maize was significantly influenced by sowing windows (factor A). Among the different sowing dates, plants established during the first fortnight of July (D3) attained the greatest height at all stages of growth, followed by those sown in the second fortnight of June (D2). In contrast, early sowing in the first fortnight of June (D1) and delayed sowing in the second fortnight of July (D4) resulted in comparatively shorter plants. This reduction in height under D1 and D4 can be attributed to unfavourable climatic conditions, such as sub-optimal rainfall distribution and temperature stress during the vegetative phase, which limited crop vigour (54). With respect to genotypes (factor B), the hybrid MAH 14-5 (H1) consistently exhibited taller plants than the hybrid Hema (H2) across all sowing windows. This superiority of MAH 14-5 reflects its higher genetic potential for biomass accumulation and better adaptation to the prevailing agro-climatic conditions.

The interactive effects of genotype × sowing window were also evident. The treatment H1D3 (MAH 14-5 sown in July first fortnight) recorded the maximum plant height at 30 days after sowing (DAS) (24.75 cm), 60 DAS (187.28 cm), 90 DAS (215.78 cm) and harvest (218.11 cm), demonstrating the favourable synchrony between genotype potential and optimum environmental conditions. Conversely, H2D1 (Hema sown in June first fortnight) produced the lowest plant height across all stages, highlighting the negative impact of early sowing under less favourable rainfall and temperature regimes. These findings confirm that aligning sowing windows with genotype adaptability is critical for enhancing plant vigour and productivity in maize (56).

### Number of leaves per plant

The number of leaves per plant was not significantly influenced by sowing windows (factor A). Although numerical differences were observed, leaf initiation and development remained relatively stable across planting dates, suggesting that this trait is less sensitive to variations in rainfall and temperature compared to other growth parameters. Similarly, genotypes (factor B) did not show significant variation in leaf number. Both MAH 14-5 (H1) and Hema (H2) produced comparable leaf counts, indicating that genetic factors exerted only a marginal effect on this parameter. However, the interactive effects revealed notable trends. The treatment H1D3 (MAH 14-5 sown in July first fortnight) recorded the highest number of leaves at 30, 60, 90 DAS and harvest (6.07, 15.12, 15.55 and 12.04, respectively), while the lowest values were observed in H2D1 (Hema sown in June first fortnight) (4.98, 11.42, 12.52 and 7.35, respectively). These results suggest that although leaf number was statistically non-significant, favourable genotype × environment interactions under H1D3 promoted better leaf retention, which could indirectly enhance canopy size and photosynthetic efficiency.

Leaf area was significantly influenced by sowing windows (factor A). The maximum leaf expansion was recorded when maize was sown in the first fortnight of July (D3), followed by the second fortnight of June (D2). Early sowing in June first fortnight (D1) and delayed sowing in July second fortnight (D4) resulted in comparatively smaller leaf areas, reflecting sub-optimal growing conditions during critical vegetative stages.

With respect to genotypes (factor B), MAH 14-5 (H1) consistently produced a larger leaf area than Hema (H2) across all sowing windows. This indicates that MAH 14-5 has greater genetic potential for canopy development and photosynthetic efficiency.

The interactive effects showed that the treatment H1D3 (MAH 14-5 sown in July first fortnight) achieved the highest leaf area at 30, 60, 90 DAS and harvest (2060.33, 7873.00, 8147.33 and 5738.33 $cm^2$/plant, respectively). Conversely, the lowest leaf area values were observed in H2D1 (Hema sown in June first fortnight) (1889.67, 5909.00, 6046.00 and 4926.33 $cm^2$/plant). These results confirm that synchrony between genotype potential and the July sowing window promoted better canopy establishment and photosynthate accumulation, thereby supporting higher yield potential.

### Effect on the yield attributes of maize

The yield attributes of maize were significantly influenced by sowing windows (factor A). Among the four sowing periods, sowing during the first fortnight of July (D3) produced the highest number of rows per cob, kernels per row and kernels per cob, whereas early sowing in the first fortnight of June (D1) resulted in the lowest values. The superior performance under D3 can be attributed to favourable rainfall distribution and optimum temperature conditions during the reproductive phase, which promoted effective pollination and kernel set. In contrast, early sowing coincided with unfavourable climatic conditions, reducing reproductive success (58). With respect to genotypes (factor B), the hybrid MAH 14-5 (H1) consistently outperformed Hema (H2) in all yield components. MAH 14-5 recorded more rows per cob and a higher kernel count, indicating its superior genetic potential to utilise available resources and withstand environmental stress during reproductive stages.

The interactive effects further highlighted the advantage of the optimum sowing window–genotype combination. The treatment H1D3 (MAH 14-5 sown in July first fortnight) recorded the maximum values for rows per cob (15.39), kernels per row (541.98) and kernels per cob (541.98). In contrast, the treatment H2D1 (Hema sown in June first fortnight) registered the lowest values (rows per cob: 12.41; kernels per row: 345.93; kernels per cob: 345.93). These findings confirm that optimum synchrony between genotype potential and favourable environmental conditions enhances yield attributes, whereas misalignment (early sowing of Hema) leads to poor kernel set and reduced productivity (57, 58).

Grain yield was significantly influenced by sowing windows (factor A). The highest yields were obtained when maize was sown during the first fortnight of July (D3), followed by the second fortnight of June (D2). Early sowing in June first fortnight (D1) and delayed sowing in July second fortnight (D4) produced comparatively lower yields. This pattern indicates that optimum rainfall distribution and moderate temperatures during July created favourable conditions for grain filling, while both early and late sowings were exposed to climatic stress that reduced productivity (58). With respect to genotypes (factor B), MAH 14-5 (H1) consistently outperformed Hema (H2) across most sowing windows. The higher yield potential of MAH 14-5 reflects its superior genetic adaptability, efficient canopy development and better conversion of assimilates into grain compared to Hema.

The interactive effects of genotype × sowing window clearly identified the best and worst treatment combinations (Fig 16). The H1D3 (MAH 14-5 sown in July first fortnight) treatment recorded the maximum yield (6810 kg/ha), followed by H2D3 (Hema sown in July second fortnight) with 6637 kg/ha. In contrast, the lowest yield was obtained from H1D1 (MAH 14-5 sown in June first fortnight) (4677 kg/ha), highlighting the negative effect of early sowing under sub-optimal rainfall. Late sowing of Hema in July second fortnight (H2D4) also produced a comparatively lower yield (4931 kg/ha). These results underline the critical importance of synchronising the sowing window with genotype adaptability to achieve maximum productivity. The remarkable performance of the H1D3 treatment in maize plant height demonstrates the successful synergy between the MAH-14-5 hybrid's genetic potential and optimal environmental conditions during the July sowing window. The consistently superior plant stature throughout the crop cycle suggests that this specific combination of maize hybrid (H1) and sowing window (D3) created ideal conditions for maximising the genetic expression of height-related traits. Key environmental factors, including temperature ranges, moisture availability, nutrient supply and growing degree days, aligned favorably during the D3 sowing window to enhance nutrient uptake and metabolic processes.

Plant heights' significance extends beyond just vertical growth, as it influences crucial agronomic characteristics including biomass accumulation, light interception and yield potential. While taller plants can increase photosynthetic surface area and improve resource utilisation efficiency, leading to higher yields, they also require careful management. The primary concern is the risk of lodging - stem breakage or leaning - which can result in significant yield losses if not properly addressed through appropriate management practices. The distinct height variations observed across treatment combinations emphasise the critical importance of identifying optimal genotype-environment pairings. This careful matching of genetic potential with environmental conditions ultimately enhances crop productivity and resource use efficiency in maize cultivation, though success depends on maintaining a balance between maximising growth potential and preventing lodging risks in commercial production settings. The patterns of leaf development observed across treatments reveal the complex interplay between genetic factors and environmental conditions (59). While the number of leaves showed some variation between treatments, more pronounced differences emerged in leaf area development, suggesting that environmental conditions during the growth period exerted a stronger influence on leaf expansion compared to leaf initiation (60). The dynamic nature of leaf development in maize was evident in the varying leaf numbers observed across different growth stages. Factors such as environmental conditions, nutrient availability and plant vigour demonstrated a more substantial impact on leaf development. This finding has important implications for understanding maize's physiological responses to different growing conditions and developing management strategies to optimise canopy development (61).

The study focused on measuring leaf area ($cm^2$/plant) in different treatments and at various time intervals. The variation in leaf area ($cm^2$/plant) at different intervals provides valuable insights into the overall growth and development of the plants. The recorded significantly higher leaf area for the MAH 14-5 sowing in the July first fortnight (H1D3) treatment indicates a robust growth pattern. On the other hand, the lowest leaf area recorded in treatment H2D1 (Hema hybrid sown in June first fortnight) suggests a comparatively slower growth rate. Understanding the dynamics of leaf area variation in different treatments over time provides crucial information about a plants' response to specific environmental conditions and treatments. Additionally, it offers valuable insights for optimising agricultural practices and maximising photosynthetic production. The superior yield parameters observed in the H1D3 treatment can be attributed to multiple factors working in concert. The timing of reproductive stage development likely coincided with favourable environmental conditions, particularly in terms of temperature and moisture availability during the critical grain-filling period (62). The higher number of kernels per cob in this treatment suggests more efficient pollination and better resource allocation during seed development, possibly due to reduced environmental stress during these critical phases (63).

This difference in the number of rows per cob is due to sowing time and hybrid variety, which is consistent with previous studies that have reported a significant impact of these factors on maize yield components. This difference in the number of rows per cob is due to sowing time and hybrid and these results are in line with previous studies that have reported a significant impact of these factors on maize yield components (64). The variation in the number of rows per cob can be attributed to the influence of environmental conditions such as temperature and moisture availability during critical growth stages of maize (65).

The number of kernels per cob, an essential factor in maize production, showed substantial heterogeneity among the treatments, caused by the interaction of genotype and sowing date. The H1D3 treatment, which involved planting the high-yielding maize hybrid MAH 14-5 in the first fortnight of July, resulted in a significantly greater number of kernels per cob (541.98). The exceptional performance of the hybrid can be attributed to its genetic potential (66) and the favourable environmental conditions during the crucial reproductive stages, specifically grain filling, under the late-sown condition (67). On the other hand, treatment H2D1, which involved planting the maize hybrid Hema in the first week of June, showed the lowest number of kernels per cob (345.93). Previous studies have found that planting crops early can lead to less-than-ideal development of kernels and grain filling. This is because increased temperatures and a lack of moisture during the reproductive stage can negatively impact the process (68). Furthermore, the hybrid Hema may exhibit a reduced genetic capacity for kernel number in comparison to MAH 14-5, which could explain the observed discrepancy (69). Multiple studies have emphasised the significance of selecting the best sowing dates and understanding the interaction between genotype and environment in order to determine the number of kernels and overall yield in maize. Strategic choice of planting dates and suitable genetic varieties can alleviate the negative impacts of environmental pressures and optimise the production of kernels and grain yield (70). Sustainable maize agroecosystems require the implementation of adaptation strategies that address the impacts of changing weather parameters and climatic conditions on crop productivity (71).

## Conclusion

The study identified four main rain phases, with the most significant rainfall occurring in the southwest and northeast corners of the district of Chamarajanagara. Rain hit hardest in these areas, affecting crop growth and farmers' time planting around them. Trend analysis revealed that rain built up slowly from southwest to northeast, with a peak in the southern tip. The authors applied spatial tools like inverse distance weighted (IDW), ordinary kriging, simple kriging and universal kriging to check their accuracy against variogram types. They found that stable and Gaussian variograms showed tight patterns, while ordinary kriging had the lowest root mean square error. Rainfall in Chamarajanagara is influenced by weather fronts, seasonal shifts, land shape and climate trends. Central and eastern spots absorb more rain, while western and northern areas receive scant drops. July is particularly beneficial for maize in lower zones, with peaks around 200 mm in the first half.

Tests showed that sowing dates shape maize growth and output. Early July, or D3, was the best window for maize growth and yields. Two hybrids, MAH 14-5 (H1) and Hema (H2), performed well in variable weather conditions, with H1 achieving higher yields on average. Genotype and sowing paired up for significant results, with H1 in early July topping the chart at 6810 kg/ha. Farmers who sync this timing can double their harvests in tough years. Future studies should evaluate these methods across multiple regions and crops, using multilocation meteorological and crop data to better understand climate change impacts on precipitation and productivity.

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## Authors' contributions

HPR and CK conceived the research idea, designed the comprehensive study framework, implemented the experiment and drafted the manuscript. SRI and MH participated in the experimental design, supervised maize genotype evaluation and contributed significantly to data interpretation and manuscript writing. HRB and VVE participated in data compilation and assisted in preliminary data analysis. VKC contributed to scientific interpretation and provided technical inputs during manuscript development. MK and NK contributed to manuscript writing and critical revision. SKGV assisted in data management and formatting of the final draft. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

## Declaration of generative AI and AI-assisted technologies in the writing process

AI assistance (ChatGPT) was used to support the writing the language refinement in the parts of the manuscript. The author reviewed, edited and verified all Al assistant content and takes full responsibility for the final version.

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