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Soil temperature prediction in the upper Gangetic Plain of India using a data-driven approach

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सार – फसल के उत्पादन और वृद्धि को प्रभावित करने वाली भौतिक-रासायनिक और जैविक प्रक्रियाओं की गतिशीलता और नियति को निर्धारित करने में मृदा तापमान महत्वपूर्ण भूमिका निभाता है। जलवायु लचीलेपन के लिए मृदा तापमान व्यवस्था पर आधारित कृषि प्रणालियों का सतत गहनीकरण आवश्यक है। वर्तमान अध्ययन में भारत में गंगा के ऊपरी मैदानों में स्थित ICAR-भारतीय गन्ना अनुसंधान संस्थान में वायु तापमान से मृदा तापमान का अनुमान शामिल है। 5, 10 और 20 सेमी गहराई पर मृदा तापमान के अनुमान के लिए डेटा-संचालित अनुभवजन्य प्रतिगमन मॉडल की पहचान की गई। सभी तीन गहराइयों पर दैनिक, साप्ताहिक और मासिक अवधि में सुबह के मृदा तापमान का अनुमान करने के लिए पावर मॉडल सबसे उपयुक्त पाया गया और 20 सेमी पर साप्ताहिक तापमान के लिए एक्सपोनेंशल मॉडल सबसे उपयुक्त पाया गया। इसके अलावा 10 और 20 सेमी की गहराई पर दैनिक, साप्ताहिक और मासिक अवधि में दोपहर के मृदा तापमान का अनुमान करने के लिए पावर मॉडल सबसे उपयुक्त था। हालांकि, 5 सेमी की गहराई पर दैनिक, साप्ताहिक और मासिक अवधि में दोपहर के मृदा तापमान का अनुमान करने के लिए एक्सपोनेंशियल मॉडल सबसे उपयुक्त था। न्यूनतम वायु तापमान सुबह के मृदा तापमान का अनुमान करने के लिए सबसे उपयुक्त था, जबकि अधिकतम वायु तापमान दोपहर के मृदा तापमान का अनुमान करने के लिए सबसे उपयुक्त था। यह पावर मॉडल 5 सेमी गहराई पर मृदा तापमान के उपयोग के माध्यम से 10 और 20 सेमी पर मृदा तापमान के अनुमान के लिए भी सबसे उपयुक्त साबित हुआ। सर्वोत्तम-फिट प्रतिगमन मॉडल की सटीकता 97.1 से 99.1% तक थी। वर्तमान कार्य परिवेशी वायु तापमान के आधार पर मृदा तापमान को अनुमानित करने के लिए उपयुक्त मॉडल प्रस्तुत करता है। यह निष्कर्ष शोधकर्ताओं, नीति निर्माताओं और किसानों के लिए कृषि पर जलवायु परिवर्तन के प्रभावों को कम करने में उपयोगी होंगे।

ABSTRACT. Soil temperature plays a crucial role in determining the kinetics and fate of physicochemical and biological processesinfluencingcrop growth and development. Soil temperature regimes based sustainable intensification of agricultural systems is needed for climate resilience. The present study involved prediction of soil temperature from the air temperature at the ICAR-Indian Institute of Sugarcane Research located in the upper Gangetic Plains of India. The data-driven empirical regression models were identified for prediction of soil temperature at 5, 10 and 20 cm depths. The power model was found the best fit for predicting daily, weekly and monthly morning soil temperature at all three depths, with the exception of exponential model, found best for weekly temperature at 20 cm. Further, power model was the best fit for daily, weekly and monthly afternoon soil temperature predictions at 10 and 20 cm. However, exponential model was the best fit for daily, weekly and monthly afternoon temperature at 5 cm depth. The minimum air temperature was most suitable for predicting morning soil temperature whereas the maximum air temperature for afternoon soil temperature. The power model also served as the best-fit for soil temperature prediction at 10 and 20 cm through the use of soil temperature at 5 cm depth. The accuracy of the best-fit regression models ranged from 97.1 to 99.1%. The present work offers appropriate models for predicting soil temperature based on ambient air temperature. The findings will be useful for researchers, policy makers and farmers to help mitigate climate change impacts on agriculture.

Key words – Soil temperature, Air temperature, Climate change, Upper Gangetic Plain, Alluvial soil.

1. Introduction

Soil temperature is one of the key meteorological parameters that influences plant physiology and crop growth (Elaboratively *et al.*, 2010; Lu *et al.*, 2009; Matthias and Musil 2012; Sandor and Fodor, 2012). It has a significant effect on the composition of organic matter, plant growth and living biota, as it directly controls the water content present in the soil (Araghi *et al.*, 2017). High spatiotemporal variability in soil temperature plays a major role in determining the rates and directions of soil physical processes and mass-energy exchange with the atmosphere (Onwuka and Mang, 2018). Every degree of change in soil temperature leads to an approximately 2% change in various soil biological, chemical, and physical properties (Onwuka and Mang, 2018). Soil temperature thus governs evaporation, aeration, and the types and rates of chemical reactions occurring in the soil (Biazar *et al.*, 2024). Thesephenomena propagate into the soil profile *via* a complex series of transport processes, the rates of which are affected by temporal and spatial variables ofsoil properties (Pierre *et al.*, 2014; Sihag *et al.*, 2020, Radvelle *et al.*, 2016). Soil temperature strongly influences biological processes such as seed germination, seedling emergence and growth, root development, and microbial activity (Imanian *et al.*, 2022).The plant available nutrientincreases with increasing soil temperature if other factors, such as moisture and aeration, are optimal (Inselsbacher and Nasholm, 2012). Additionally, soil temperature differs daily, weekly, monthly and seasonally due to changes in incident radiation and energy exchange at the soil surface as a result of the exchange of gases between the atmosphere and the soil (Onwuka and Mang, 2018).

Soil temperatures between 10 and 36.6 °C are necessary for the majority of biological processes because microorganisms need that range to function normally (Conant *et al.*, 2008 & 2011). Gomez *et al.*, (2020) reported that soil temperatures between 10 and 28 °C increase extracellular enzymatic activities and microbial retention of soluble substrates that degrade polymeric organic matter in soil through increased nitrogen mineralization and phosphorus solubilisation processes (Yan and Yangwen, 2014; Zhang *et al.*, 2019). Reports have indicated that at exceedingly high soil temperatures (58 °C), beneficial soil microorganisms are dead (Onwuka and Mang, 2018). However, sub-zero soil temperatures cease microbial activities and slow biochemical processes, causing greater accumulation of soil organic matter (Allison *et al.*, 2010). Soil temperatures below 5 °C have been shown to lead to negligible root extension and hinder the release of phosphorus from organic matter (Horton and Ochsner, 2011; Yilvainio and Pettovvuoori, 2012; Shirvani *et al.*, 2018).

Extreme low and high soil temperatures have adverse impacts on various crops (Oliveira *et al.*, 2001). It is thus necessary to attempt to sustainably intensify agricultural systems in accordance with the soil temperature dynamics (Luo *et al.*, 2020). An effective adaptation to climate change-induced alterations in crops can be achieved by developing location-specific precision agronomic packages based on local soil temperature predictions (Verma *et al.*, 2019; Srivastava *et al.*, 2022). However, information on the influence of varying soil temperature regimes at different soil depths is essential for understanding physical, biological and chemical changes under changing climatic scenarios and their impact on the growth and development of crop plants at different growth stages (Mampitiya *et al.*, 2024). Regions delineated on the basis of agro-ecological similarities however, witness climatic variabilities both in time and space dimensions that makes availability of location specific soil temperature data essential for devising precision farming tools and techniques in order to effectively adapt to climate change.Practical implications of understanding and regulating the soil temperature have been witnessed in devising agronomic management practices such as residue retention and recycling, reduced tillage, variable rate of nutrient application. Regulation of soil temperature by cover crops and residue mulching have been found to influence microbial activity and nutrient availability (Hu and Feng, 2003). A general lack of recording of soil temperature data in the region and other similar regions elsewhere necessitates the prediction of such data using various approaches. Several numerical models have been proposed for complex heat and mass transport in soil, implying that soil moisture has a role in determining soil temperature (Narsimhan, 2005). Barman *et al.*, (2017) reported that soil temperature, which is directly related, can be predicted by using air temperature through empirical regression models. Developments in computer science and artificial intelligence (AI) have led to the development of data-driven models based on data mining, *i.e.*, discovering patterns in data based on techniques such as artificial neural networks (ANNs), adaptive neuro-fuzzy inference systems (ANFISs) and M5 tree models for the prediction of soil temperature (Quinlan, 1992; Sattari *et al.*, 2017). AI including Machine Learning (ML) have been found practically applicable for soil texture prediction and soil health management as these approached not only save the time but also effectively reduce the expenditure on soil sampling, processing and data generation. However, challenges related to quality of non-numerical data, data interpretability, and system integration will be crucial for the successful implementationof AI-based soil analysis (Liu *et al.* 2023). Regression-based models are being used effectively for computational ease and precision in the estimation of soil temperature at varying soil depths and time scales for daily to yearly predictions. Empirical models were found to be fairly good at predicting soil temperature at any location considering the soil moisture, climatic conditions and land use patterns of the region (Barman *et al.*, 2017; Dolschak *et al.*, 2015; Kang *et al.*, 2000).There are weaknesses of regression based models as well, these models are sensitive to outliers, and it is assumed that errors are equally distributed which seldom occur in soil related studies considering variability in soil properties and influence of climatic conditions. Nevertheless, regression models have been extensively used for predictive modelling of crop nutrition and water management, soil variability mapping and crop yield estimation.Since the availability of soil temperature data is limited at the spatiotemporal scale, the air temperature has been used as an independent variable to predict soil temperature in the present study. The objective of the

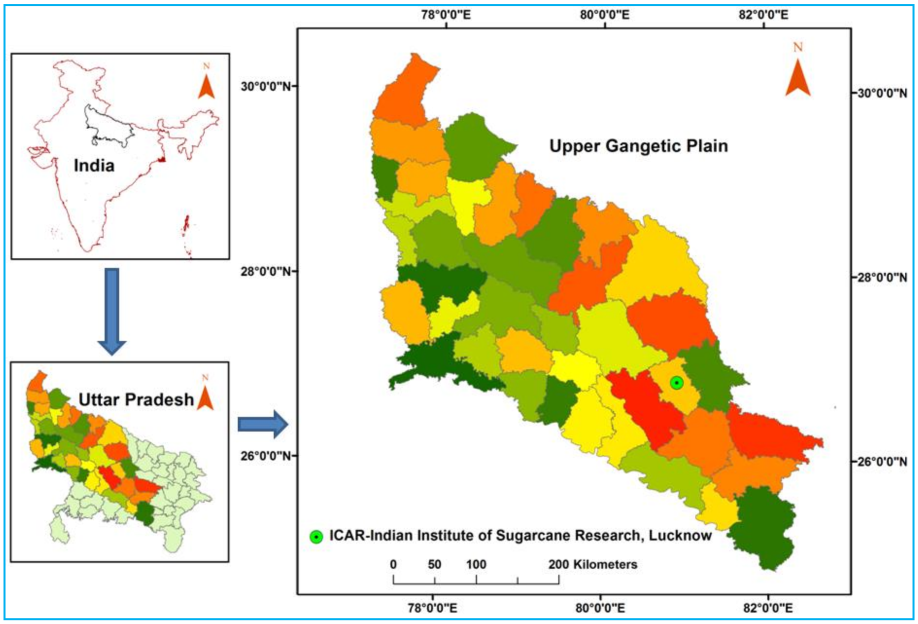


Fig. 1. Location map of study area

present study was to find best fit regression models to predict soil temperature at various soil depths on daily, weekly, seasonal and annual basis. The identified models can be effectively used to predict soil temperatures based on ambient air temperature to facilitate the development of location specific precision farming techniques. This will further help deploying the climate resilient agricultural tools and techniques in the areas where soil temperature data is not available. The findings have a scope for wide scale use by researchers, farmers and policy makers to sustainably intensify the agriculture.

2. Data and methodology

2.1. *Study site*

The study site is located in the upper Gangetic Plain (UGP) zone that occupies about 60 % of the geographical area of Uttar Pradesh (UP), an agriculturally important state in north India (Fig. 1). UP, India's most populous province, is represented by this zone and contributes approximately 22% of the country's total food grain production. Soils of the UGP zone were formed with an alluvium brought by the Ganga River and its tributaries and occupy approximately 20 million hectares (m ha), of which about 15 m ha is cultivated with various cereals, pulses, oilseeds and forage crops, which are grown in well-defined crop rotations of one to three years cycle. Texturally, varying from sandy to clay loam, these soils belong to the soil order *Inceptisol* and are low to medium in soil organic carbon, deficient in nitrogen content and neutral to alkaline in reaction. Because of their proximity to the Himalayas, plain soils are extremely sensitive to seasonal and annual weather variations. The plain is characterized by wide temperature variations in different seasons, ranging from a mean temperature of approximately 2-3 °C in winter to approximately 45 °C in summer, with an average annual rainfall of 900-1200 mm (Narsimhan, 2005). It has a table-top appearance with an average altitude of 168 m and rises in elevation from east to west and south to north with an average increase of 2 m km^{-1} in distance.

The soil and air temperature data used in the study were recorded at the meteorological observatory of the ICAR-Indian Institute of Sugarcane Research (IISR), Lucknow, from 1991-2020. The site is located at26° 80' N, 80° 94' E and 111 m above mean sea level (Fig. 1). The soils of the study area are alluvial-derived, very deep (> 2 m), well-drained, flat and classified as non-calcareous mixed hyperthermic *udicustochrept*. The climate of the site is semiarid and subtropical with hot, dry summers and cold winters. On the basis of the average monthly air temperature, January was the coldest month of the year, and May was the hottest month of the year. The long-term average annual rainfall at the site is 948.8 mm, which is mainly received through the southwest monsoon (June – September). Air temperature data were recorded through a mercury thermometer installed on a Stevenson screen positioned at a height of 1.2 metres from the ground, while soil temperature data were recorded with mercury soil thermometers installed at soil depths of 5, 10 and 20 cm at the agro meteorological observatory, ICAR-IISR, Lucknow, India. The air and soil temperature data were recorded daily at 07:18 and 14:18 IST. The minimum

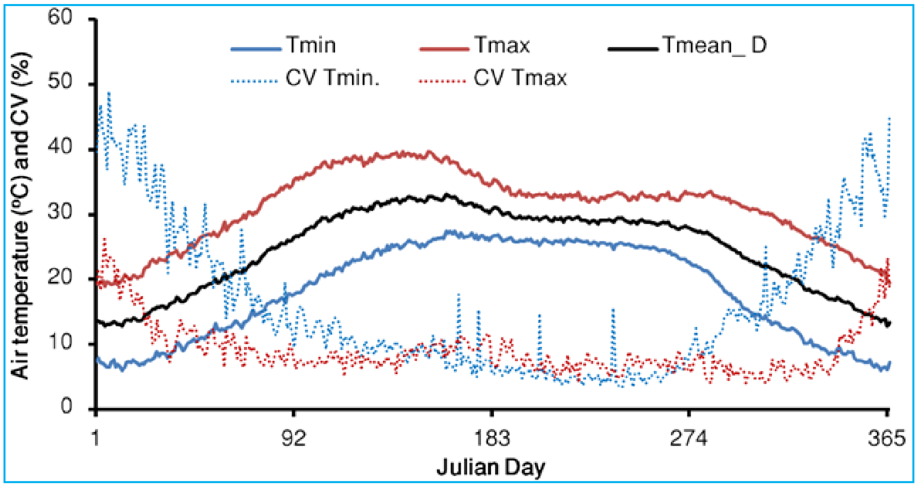


Fig. 2. Daily air temperature pattern of 30 years recorded during 1991-2020 in upper Gangetic plains of India

temperature recorded by the minimum thermometer in a day represents the minimum temperature, and similarly, the maximum temperature recorded by the maximum thermometer in a day represents the maximum temperature. Standard statistical methods were used to transform the daily soil temperature to average weekly, monthly, seasonal and annual data. Soil samples from the soil temperature recording site were collected within a radius of 1 meter from the location where the soil thermometer was installed and the soil texture was analysed by following the method of Bouyoucos, (1962). The textural class of the site was silty loam with mechanical soil particles; sand, silt and clay were present at 19.00, 62.00, and 18.48%, respectively, up to 20 cm soil depth.

2.2. *Statistical analysis*

The mean, standard deviation and coefficient of variation of daily, weekly, monthly, seasonal and annual air and soil temperature data were analysed by using SPSS software version 20.0. The magnitudes and trends in the monthly minimum, maximum and mean air temperatures and monthly soil temperature data recorded in the morning and afternoon at the 5, 10 and 20 cm soil depths were analysed with the nonparametric Mann–Kendall method (Djamana*et al.*, 2016; Kendall, 1975; Mann, 1945) by using RStudio software (RStudio Team, 2020). This method is widely accepted for its efficiency (Srivastava *et al.*, 2021). In this method, the static S is computed as:

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \operatorname{sign}\left(x_i - x_j\right)$$

where x_i is the data value at time i, n is the length of the dataset and sign (x_i-x_j) is the sign function, which can be computed as –

$$\operatorname{Sign}\left(x_i - x_j\right) = \begin{bmatrix} 1 \text{ if } \left(x_i - x_j\right) > 0 \\ 0 \text{ if } \left(x_i - x_j\right) = 0 \\ -1 \text{ if } \left(x_i - x_j\right) < 0 \end{bmatrix}$$

For n>10, the test statistic Z approximately follows a standard normal distribution:

$$Z = \begin{bmatrix} \dfrac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{bmatrix}$$

The Var (S) is the variant of the statistic S. The value of Z shows the type of trend in the data series. An increasing trend in the data is shown by its positive Z values, whereas a declining trend in the data series is indicated by its negative Z values. In the present method, the null hypothesis (H_0) was considered, as there is no trend in the time series data and against its alternative hypothesis ($H1$) for a negative or positive trend in the time series data. The test of significance of the data was performed at the 5% level.

The various nonlinear regression models were tested for the prediction of soil temperature (Y_t) at time points t = 1, 2, ...n in the morning and afternoon at 5, 10 and 20 cm soil depths with minimum, maximum and mean daily, weekly and monthly air temperatures, respectively. The

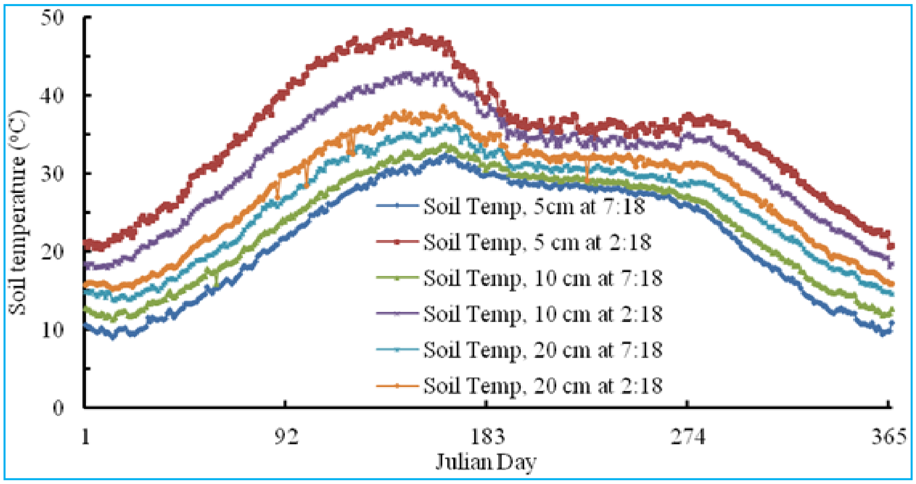


Fig. 3. Daily soil temperature pattern of 30 years recorded during 1991-2020 in upper Gangetic plains of India

statistical analysis of nonlinear regression models was performed by using SPSS software version 20. The models used in the study were power, exponential and logarithmic. The most suitable models were selected for the prediction of soil temperature in the morning and afternoon at different depths based on the higher regression coefficient values of the models.

3. Results and discussion

3.1. *Soil and air temperature status in the upper Gangetic Plain*

Air and soil temperature data were analysed for characterization and deciphering the relationships between these two variables at daily, weekly, monthly, seasonal and annual bases. The average daily minimum, maximum and mean air temperature data for the 30 years period (1991-2020) are presented in Fig. 2. The minimum temperature at the bottom and maximum temperature at the top and the mean daily air temperature are shown in the middle of the graph. Temperature was recorded lower during the winters and high in the summer season. During the period the lowest minimum daily temperature was -0.08 °C, the lowest maximum air temperature was 8.40 °C and the lowest mean air temperature was 5.6 °C. The highest coefficient of variation range occurred for the minimum air temperature (from 3.37 to 48.98%), followed by the maximum air temperature (from 4.07 to 26.21%) and mean air temperature (from 3.51 to 25.14%). These results showed that the maximum air temperature has been more consistent over the last three decades, but the minimum air temperature has shown wide variation. Our results are corroborated by those of Ren *et al.* (2017), who observed changes in surface air temperature in the Hindu Kush Himalayan region and reported that the diurnal temperature range (DTR) showed a significant negative td of -0.1 °C per decade due to the much greater increase in the minimum air temperature than in the maximum air temperature in the region.

The daily minimum, maximum and mean air temperature data were converted to meteorological weeks (SMW) by statistical means. The SMW data revealed that the lowest daily minimum, maximum and mean air temperature values were 2.29, 12.21 and 8.14 °C, respectively, during the second SMW (8-14 January). The corresponding highest daily mean minimum temperature was 29.89 °C during the 20th SMW (14-20 May), the mean maximum temperature was 44.26 °C during the 22nd SMW (28 May-03 June) and the mean daily temperature was 36.33 °C during the 24th SMW (11-17 June). Subsequent SMWs following 24th SMW recorded lower mean daily temperature and lesser diurnal variability till the year end. Barman *et al.*, (2012 & 2017) reported similar results in the lower Gangetic Plains of India and indicated that the minimum and maximum air temperatures were low in July. Less air temperature variability during this period than during the rest of the year is the result of monsoons entering the upper Gangetic Plain in the 3rdweek of June. Rains cool the air temperature in the region for a brief span of time on a given day because the temperature of water droplets is supposed to be less than that of the subjected air (Islam *et al.*, 2015). As marked by the daily temperature variability, the weekly minimum temperature also exhibited greater variability (from 2.51 to 31.18%) than did the weekly maximum temperature (from 3.35 to 18.50%). Amongst the SMWs, the lowest CV value for minimum air temperature was recorded for 31st SMW (30th July to 5th August), and the lowest CV value for maximum air temperature was recorded at 32nd SMW (6th

TABLE 1

Descriptive analysis of monthly minimum, maximum and mean air temperatures recorded during 1991-2020

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Summer	Monsoon	Winter	Annual
Tmin (°C)																
Mean	7.30	10.51	15.08	20.55	24.70	26.56	26.04	25.64	24.36	18.53	12.03	7.87	20.12	25.65	11.25	18.26
SD	1.23	1.20	1.14	1.11	0.88	0.79	0.69	0.61	0.79	1.33	1.17	1.15	0.71	0.49	0.62	0.50
CV (%)	16.85	11.42	7.56	5.40	3.56	2.97	2.65	2.38	3.24	7.18	9.73	14.61	3.53	1.91	5.51	2.74
Tmax (°C)																
Mean	20.64	25.15	31.31	37.19	38.87	37.27	33.45	32.74	32.75	32.19	28.27	23.06	35.79	34.04	25.86	31.07
SD	2.03	1.74	1.53	1.66	1.31	2.22	1.10	0.71	1.15	1.17	0.81	1.55	1.06	0.73	0.88	0.50
CV (%)	9.84	6.92	4.89	4.46	3.37	5.96	3.29	2.17	3.51	3.63	2.87	6.72	2.96	2.14	3.40	1.61
Tmean (°C)																
Mean	13.98	17.83	23.2	28.86	31.78	31.93	29.74	29.19	28.54	25.36	20.14	15.46	27.94	29.84	18.55	24.68
SD	1.24	1.25	1.17	1.23	0.84	1.43	0.81	0.47	0.8	0.96	0.76	0.8	0.78	0.48	0.58	0.46
CV (%)	8.87	7.01	5.04	4.26	2.64	4.48	2.72	1.61	2.80	3.79	3.77	5.17	2.79	1.61	3.13	1.86

to 12th August) in the upper Gangetic Plains. Varikoden and Revadekar, (2019) reported that the highest number of rain events in the Indian subcontinent occurred in July, followed by June and August and that the lower air temperature variability was due to the increase in relative humidity driven by monsoon rains.

The average soil temperature from 1991-2020 on a daily basis at 5, 10 and 20 cm soil depths is given in Fig. 3. The daily soil temperature revealed a pattern similar to that of the air temperature at different magnitudes. The average daily minimum soil temperatures of 2.5, 5.6 and 10.0 °C at 5, 10 and 20 cm soil depths, respectively, were greater than the minimum air temperature. However, the average afternoon minimum soil temperatures at the 5, 10 and 20 cm soil depths were 9.20, 10.90 and 11.70 °C, respectively, which were higher than therespective lowest maximum air temperatures. Fig. 3 reveals that the morning average daily soil temperature was lowest in the surface soil (5 cm soil depth) and increased gradually with increasing soil depth (10 and 20 cm). This difference can be attributed to the relatively unhindered dissipation of heat energy from the bare soil, which causes faster cooling of the surface soil at night than from the subsurface soil (Dwyer *et al.*, 1990; Toy *et al.*, 1978; Kang *et al.*, 2000; Onwuka and Mang, 2018).

The afternoon soil temperature showed a decreasing trend with increasing soil depth. This is explained by the transformation of heat from energy received by solar radiation and increased soil surface temperature by the advection of hot air (Khamidov *et al.*, 2023). Similar trends were also observed for the weekly and monthly soil temperatures. The lowest weekly minimum soil temperature, 3.11 °C at the 5 cm soil depth, was recorded in the 1st SMW (1-7 January), 9.17 °C at the 10 cm soil depth in the 2nd SMW (8-14 January) and 11.27 °C at the 20 cm soil depth in the 3rd SMW (15-21 January) of the year. Similarly, the afternoon minimum soil temperatures were 11.24 °C at 5 cm in the 5th SMW (29 January to 4 February), 13.53 at 10 cm and 11.93 °C at 20 cm soil depth in the 3rd SMW (15-21 January). The weekly highest soil temperatures were 35.97, 37.91 and 39.27 °C at the 5, 10 and 20 cm soil depths, respectively, in the morning and showed an increasing trend with increasing soil depth at the 24th SMW (11-17 June). Islam *et al.*, (2015) substantiated the relationship between air and soil temperatures within a system boundary in Bangladesh. The afternoon soil temperature was highest at 53.04 °C on the 25th SMW (18-24 June) at 5 cm, 46.93 °C on the 23rd SMW (04-10 June) at 10 cm and 41.61 °C on the 24th SMW (11-17 June) at 20 cm. Thus, it was discernible that the highest soil temperature in the afternoon decreased with increasing soil depth. Soil heats from the sun during the day and cools during the night; therefore, the maximum soil temperature variability was observed in the surface soil (at 5 cm depth) compared to the subsurface soil at 10 and 20 cm soil depths. These findings were corroborated by the higher coefficient of variation range in the soil temperature data recorded in the morning (3.66-25.77%) and afternoon (6.19 to 16.08%) at the 5 cm soil

TABLE 2

Sen's slope (Q) and p value (*p* = 0.05) for the Mann-Kendall trend test of monthly minimum, maximum and mean air temperatures recorded during 1991 to 2020

Month	Tmin		Tmax		Tmean	
	Q	*p* value	Q	*p* value	Q	*p* value
January	0.023	0.520	-0.005	0.317	-0.014	0.604
February	0.028	0.362	-0.022	0.617	0.000	0.929
March	0.023	0.326	0.008	0.830	0.000	0.733
April	0.047	0.493	0.000	0.929	0.019	0.421
May	-0.143	0.475	-0.012	0.668	0.000	0.872
June	-0.008	0.617	0.238	0.532	0.011	0.681
July	-0.001	0.400	0.000	0.816	-0.013	0.325
August	0.000	0.719	0.039	0.013*	0.013	0.157
September	0.033	0.065	0.047	0.074	0.033	0.039*
October	0.008	0.748	0.031	0.362	0.026	0.174
November	0.015	0.475	-0.008	0.579	0.007	0.566
December	0.029	0.211	-0.039	0.040*	-0.004	0.788
Summer	0.019	0.211	0.000	0.972	0.005	0.747
Monsoon	0.000	0.843	0.002	0.224	0.007	0.508
Winter	0.028	0.028*****	-0.015	0.464	0.000	0.943
Annual	0.020	0.148	0.001	0.986	0.001	0.901

*Significant at 5% level (*p*=0.05).

depth than at the deeper layers. Our finding of higher soil temperature in the afternoon than in the air temperature was also corroborated by Costa *et al.*, (2023).

The monthly, seasonal and annual minimum, maximum and mean air temperature data averaged for the 30 years (1991-2020) are presented in Table 1. Among the months of the year, the lowest minimum (7.30 °C), maximum (20.64 °C) and mean (13.98 °C) air temperatures were recorded in January, which indicated that January is the coolest month of the year in the Gangetic Plain. Similarly, although the highest maximum air temperature of 38.87 °C was recorded in May, June was recorded as the hottest month in the region due to having the highest mean monthly air temperature of 31.93 °C. These findings for the coolest and hottest months in the Indo-Gangetic Plains have also been reported by several previous researchers (Singh *et al.*, 2002; Verma *et al.*, 2019 and Kutty *et al.*, 2020). The highest variability in the mean monthly minimum, maximum and mean air temperature was recorded in January, with coefficients of variation of 16.85, 9.84 and 8.87%, respectively. However, the lowest variability of all three parameters was recorded in August, with coefficients of variation of only 2.38, 2.17 and 1.61%, respectively. The minimum variation in the month of August may be attributed to the monsoon rain-driven increase in relative humidity.

The seasonal average air temperature data revealed that the lowest minimum air temperature was recorded in the winter season (11.25 °C), followed by the summer season (20.12 °C), and the highest was found in the monsoon season (25.65 °C). However, the mean maximum air temperature was highest during the summer season (35.79 °C), followed by the monsoon season (34.04 °C), and the lowest value was found in the winter (25.86 °C). Similarly, the average mean air temperature was highest during the monsoon season (29.84 °C), followed by summer (27.94 °C) and winter (24.08 °C). The average annual minimum, maximum and mean air temperatures were 18.26, 31.01 and 24.68 °C, respectively. The seasonal air temperature findings were also supported by Sawaisarje*et al.*, (2014) in the Indo-Gangetic Plains. A time series trend analysis of the monthly minimum, maximum and mean air temperatures is given in Table 2. The trend analysis revealed a significant increasing trend in the monthly maximum and

TABLE 3

Descriptive analysis of average monthly soil temperature (°C) recorded at 5, 10 and 20 cm soil depths during 1991 to 2020

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Summer	Monsoon	Winter	Annual
Depth 5 cm at 0718 hr IST																
Mean	9.97	13.02	18.46	24.89	29.61	31.16	29.03	28.23	27.03	22.74	16.10	11.37	24.32	28.86	14.64	21.80
SD	1.24	1.07	1.15	1.32	1.06	1.53	0.88	1.04	0.97	0.85	1.05	1.02	0.99	0.86	0.50	0.63
CV (%)	12.44	8.22	6.23	5.30	3.58	4.91	3.03	3.68	3.59	3.74	6.52	8.97	4.07	2.98	3.42	2.89
Depth 10 cm at 0718 hr IST																
Mean	12.22	15.37	20.82	26.85	31.35	32.57	29.98	29.14	28.00	24.38	21.34	13.59	26.33	29.96	17.48	23.83
SD	1.19	1.38	1.21	1.15	1.14	1.65	1.42	0.53	0.60	0.76	1.03	0.83	1.00	0.79	0.82	0.69
CV (%)	9.74	8.98	5.81	4.28	3.64	5.07	4.74	1.82	2.14	3.12	4.83	6.11	3.80	2.64	4.69	2.90
Depth 20 cm at 07:18 IST																
Mean	14.49	17.53	23.57	29.90	33.88	34.76	31.37	30.65	29.38	27.03	21.40	16.48	29.02	31.58	19.35	25.80
SD	1.02	0.98	1.26	1.34	1.24	1.46	0.78	0.81	0.78	0.94	0.93	0.57	0.93	0.66	0.69	0.55
CV (%)	7.04	5.59	5.35	4.48	3.66	4.20	2.49	2.64	2.65	3.48	4.35	3.46	3.20	2.09	3.57	2.13
Depth 5 cm at 1418 hr IST																
Mean	22.11	27.87	35.99	43.83	47.02	44.40	37.25	36.15	35.75	35.70	30.01	23.84	42.28	37.68	28.03	35.06
SD	2.62	2.99	3.08	3.08	2.97	4.00	2.36	1.66	2.55	2.62	2.35	2.27	2.82	2.11	2.02	1.79
CV (%)	11.85	10.73	8.56	7.03	6.32	9.01	6.34	4.59	7.13	7.34	7.83	9.52	6.67	5.60	7.21	5.11
Depth 10 cm at 14:18 IST																
Mean	19.05	23.98	30.88	37.64	41.55	40.81	35.40	34.19	33.85	32.88	26.84	21.11	36.69	36.09	24.79	31.55
SD	1.74	1.65	2.00	2.07	2.09	3.00	1.89	1.41	1.43	1.58	1.22	1.34	1.83	1.17	1.22	1.09
CV (%)	9.13	6.88	6.48	5.50	5.03	7.35	5.34	4.12	4.22	4.81	4.55	6.35	4.99	3.24	4.92	3.45
Depth 20 cm at 1418 hr IST																
Mean	15.94	19.47	25.85	32.49	36.39	36.60	32.92	32.09	31.36	29.36	23.45	18.08	31.58	33.24	21.26	27.83
SD	1.24	1.23	1.23	1.47	1.55	1.80	1.05	1.18	0.88	1.21	1.01	0.70	1.17	0.68	0.95	0.71
CV (%)	7.78	6.32	4.76	4.52	4.26	4.92	3.19	3.68	2.81	4.12	4.31	3.87	3.70	2.05	4.47	2.55

mean air temperatures in August and September at rates of 0.013 and 0.039 °C per year, respectively. However, a significant declining trend was recorded in the maximum air temperature at a rate of -0.039 °C per year in December. A significant increasing trend in the maximum air temperature in the month of August in the Indo-Gangetic Plains was also reported by Srivastava *et al.*, (2021) based on long-term data.

The mean monthly, seasonal and annual soil temperature data recorded at two fixed times (7.18 and 14.18 IST) for the period of 30 years (1991-2020) are given in Table 3. The monthly average morning soil temperatures at depths of 5, 10 and 20 cm were the lowest at 9.97, 12.22 and 14.49 °C, respectively, with standard deviations of 1.24, 1.19 and 1.02, respectively, in January. The corresponding highest values of 31.16, 32.57 and 34.76 °C, with standard deviations of 1.53, 1.65 and 1.46, respectively, were recorded in June. The highest coefficients of variation, 12.44, 9.74 and 7.04%, recorded at the 5, 10 and 20 cm soil depths, respectively, occurred in the month of January. However, the minimum coefficients of variation for soil temperature at 5, 10 and 20 cm soil depths were recorded in September (3.59%), August (1.82%) and July (2.49%), respectively. The monthly average afternoon soil temperatures at the 5, 10 and 20 cm soil depths were the lowest at 22.11, 19.05, and 15.94 °C, respectively, with standard deviations of 2.62, 1.74 and 1.24, respectively, in January. However, the highest values of 47.02, 41.55 and 36.60 °C, with standard deviations of 2.97, 2.09 and 1.80, respectively, were recorded in May, except at the 20 cm soil depth, which was recorded in June. The highest coefficients of variation in the monthly average afternoon soil temperature at the 5,

TABLE 4

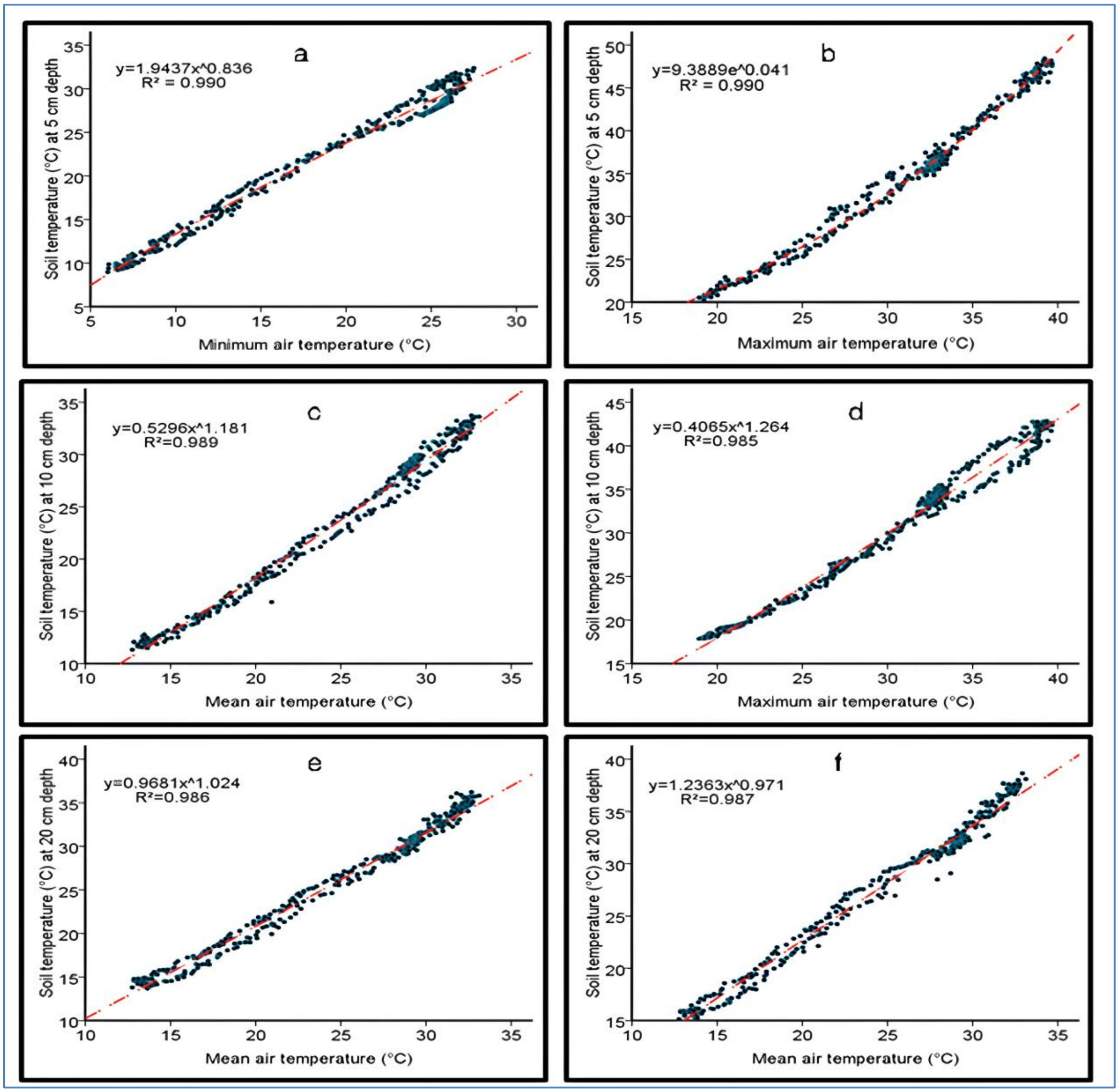
Sen's slope (Q) and p value of Mann-Kendall trend test for monthly soil temperature recorded at 07:18 and 14:18 IST for 5, 10 and 20 cm soil depths during 1991-2020

Month	Soil depth 5 cm				Soil depth 10 cm				Soil depth 20 cm			
	07:18 h		14:18 h		07:18 h		14:18 h		14:18 h		14:18 h	
	Q	*p* value	Q	*p* value	Q	*p* value	Q	*p* value	Q	*p* value	Q	*p* value
Jan	0.002	0.421	0.011	0.866	-0.140	0.216	-0.026	0.536	-0.134	0.193	-0.015	0.210
Feb	0.019	0.324	0.005	0.910	-0.094	0.410	0.010	0.793	-0.087	0.451	-0.097	0.436
Mar	0.004	0.844	0.024	0.750	0.017	1.000	0.029	0.626	0.028	0.945	0.001	0.585
Apr	0.001	0.858	0.047	0.488	0.025	0.815	-0.020	0.587	0.018	0.756	-0.067	0.585
May	-0.017	0.352	0.028	0.389	0.000	0.938	0.023	0.652	-0.002	1.000	-0.071	0.756
Jun	0.018	0.592	0.078	0.377	-0.001	0.480	0.035	0.612	-0.001	0.436	-0.026	0.101
Jul	-0.014	0.260	-0.092	0.091	-0.133	0.072	-0.095	0.018*	-0.126	0.054	-0.186	0.028*
Aug	0.000	0.788	-0.065	0.143	-0.107	0.271	-0.077	0.041*	-0.110	0.246	-0.113	0.157
Sep	0.028	0.053	0.025	0.735	0.003	0.743	0.000	0.925	0.003	0.743	-0.002	0.741
Oct	0.005	0.591	0.031	0.721	0.008	0.869	-0.005	0.368	0.001	0.913	-0.043	0.442
Nov	-0.029	0.245	-0.053	0.382	-0.078	0.271	-0.072	0.012*	-0.065	0.274	-0.125	0.124
Dec	0.023	0.283	-0.006	0.859	-0.005	0.206	-0.029	0.214	-0.053	0.228	-0.055	0.206
Summer	-0.005	0.654	0.027	0.523	0.004	0.754	-0.006	0.778	0.038	0.756	0.001	0.638
Monsoon	0.000	1.000	-0.022	0.548	-0.008	0.114	-0.038	0.113	-0.076	0.120	-0.175	0.002*
Winter	0.011	0.360	-0.015	0.586	-0.001	0.242	-0.032	0.394	-0.105	0.213	-0.133	0.182
Annual	0.001	0.887	-0.013	0.524	-0.001	0.242	-0.033	0.303	-0.007	0.161	-0.142	0.087

10 and 20 cm soil depths were 11.85, 9.13 and 7.78%, respectively. However, the lowest coefficient of variation was found in August (4.59 and 4.12%) at the 5 and 10 cm soil depths, respectively and in September (2.81%) at the 20 cm soil depth.

The average annual afternoon soil temperatures of 35.06, 31.55 and 27.83 °C were greater than the morning soil temperatures (21.80, 23.83 and 25.80 °C) at the 5, 10 and 20 cm soil depths, respectively (Table 3). There was greater variability in the average monthly soil temperature at the 5 cm soil depth in the afternoon than in the morning, except in January, when the opposite trend was observed. The seasonal average soil temperature revealed that the highest average soil temperature in the morning occurred during the monsoon season (28.86, 29.96 and 17.48 °C), followed by the summer season (24.32, 26.33 and 29.02 °C), and the lowest temperature occurred in the winter season (14.64, 17.48 and 19.35 °C) at the 5, 10, and 20 cm soil depths, respectively. The soil temperature in the morning increased with increasing soil depth. Similarly, the afternoon seasonal soil temperature was highest during the summer season (42.28 and 36.69 °C) at the 5 and 10 cm soil depths, respectively. However, at the 20 cm soil depth, the highest soil temperature occurred during the monsoon season (33.24 °C). The afternoon soil temperature decreased with increasing soil depth. Overall, the winter season recorded the lowest temperature in the morning and afternoon compared to the other seasons at all the soil depths.

The results of the trend analysis of the monthly, seasonal and annual soil temperatures given in Table 4 revealed a significant decreasing trend in the afternoon soil temperature at the 10 cm soil depth in July, August and November at rates of -0.095, 0.077 and - 0.072 °C y^{-1}, respectively. A significant decreasing trend in the afternoon soil temperature at a rate of -0.186 °C y^{-1} was also recorded at a soil depth of 20 cm in July. This significant decreasing trend was also recorded for the afternoon soil temperature during the monsoon season at a rate of -0.175 °C y^{-1}. The change in the angle of incident radiation with the changing months and seasons during a year, the resulting alternation in the day length, the variability in the relative humidity of air and the insulating effect of soil appear to have a direct role in the trend of soil temperatures during the morning and afternoon hours. A significant decreasing trend in afternoon soil

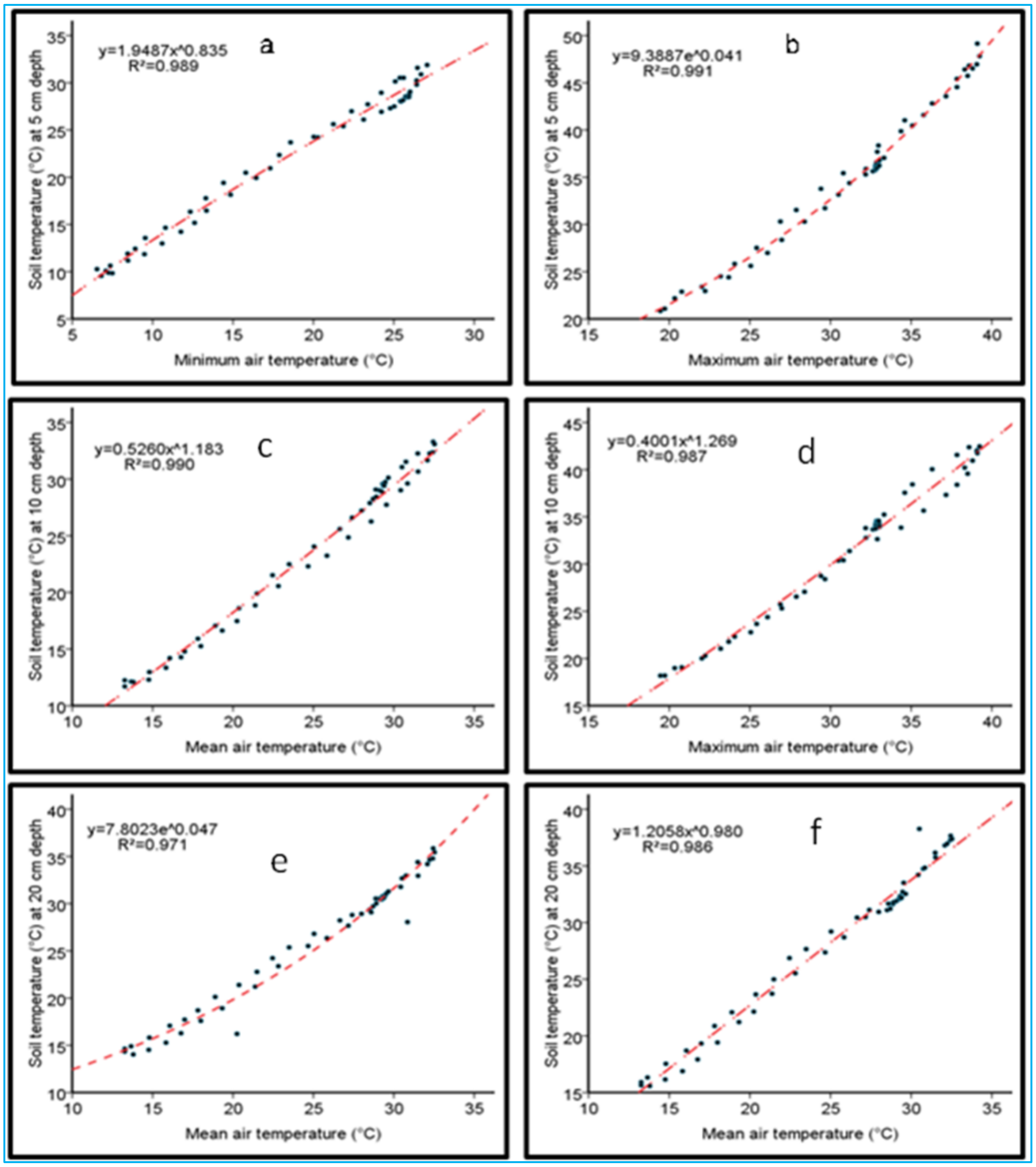


Figs. 4(a-f). Best-fit regression models (power except for 4.b that is exponential) for prediction of daily soil temperature with air temperature in morning (a, c and e) and afternoon (b, d and f) at 5, 10 and 20 cm depths

temperature at different depths was reported by Barman *et al.*, (2017) in the alluvial soils of the lower Indo-Gangetic Plains of India.

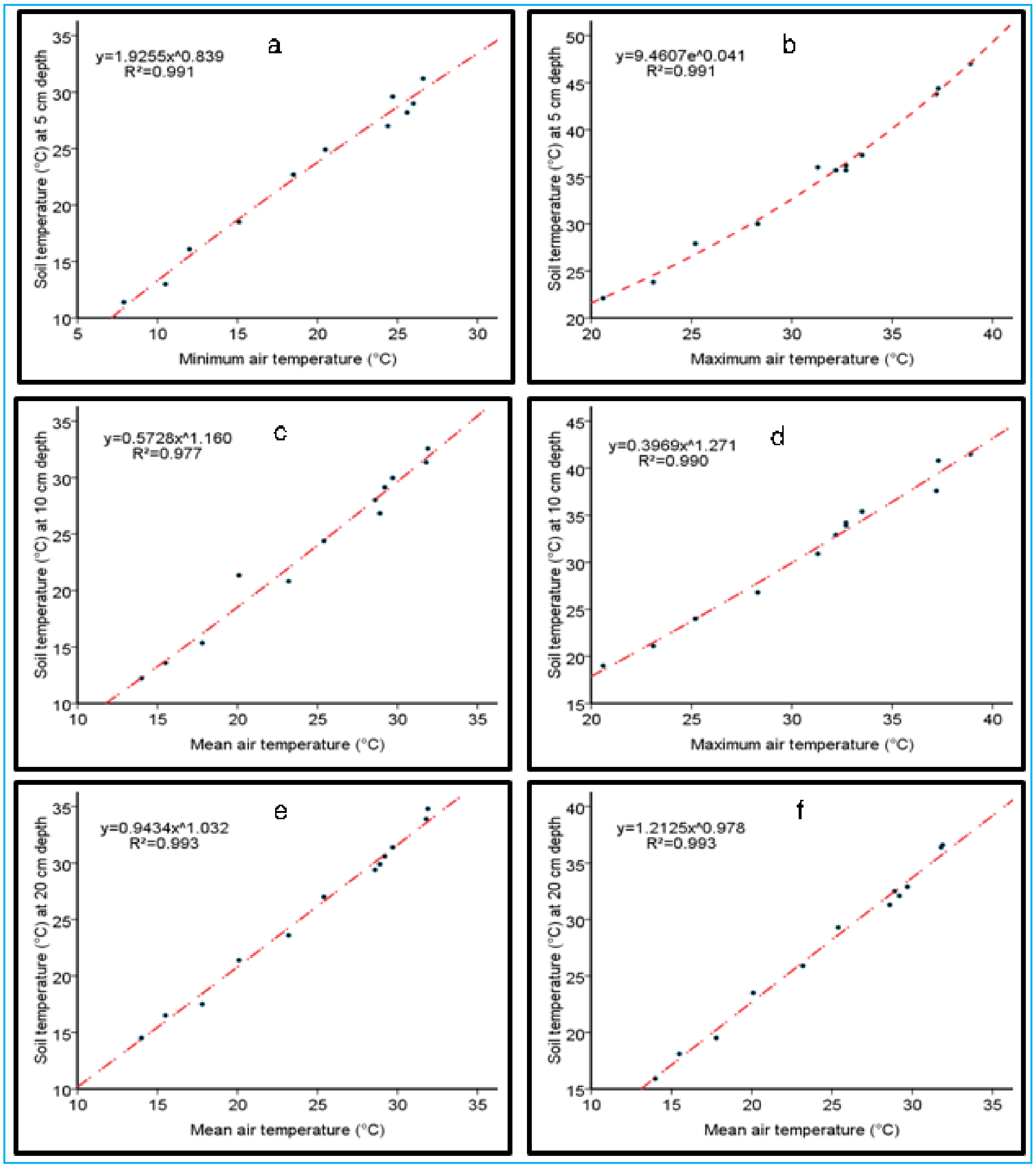
3.2. *Regression models for prediction of soil temperature*

Empirical models for the prediction of soil temperatures at different depths were developed based on regression analysis. The air temperature (minimum, maximum and mean) and soil temperature (at 5, 10 and 20 cm soil depths) data recorded during 1991-2020 were used to develop regression models. The long-term air and soil temperature data were considered with the aim of reducing the bias in the prediction of soil temperature and annual variation in temperature due to climate and soil factors (Dwyer *et al.*, 1990; Taheri *et al.*, 2023). Analysis of nonlinear regression models for the prediction of daily soil temperature based on air temperature data revealed that minimum air temperature can reliably be used to predict the soil temperature at 5 cm in the morning (07.18 IST) with the best fitted power model, with an R^2 value of 0.990 [Fig. 4(a)]. However, the maximum air temperature can be used to predict the afternoon (14.18 IST) soil



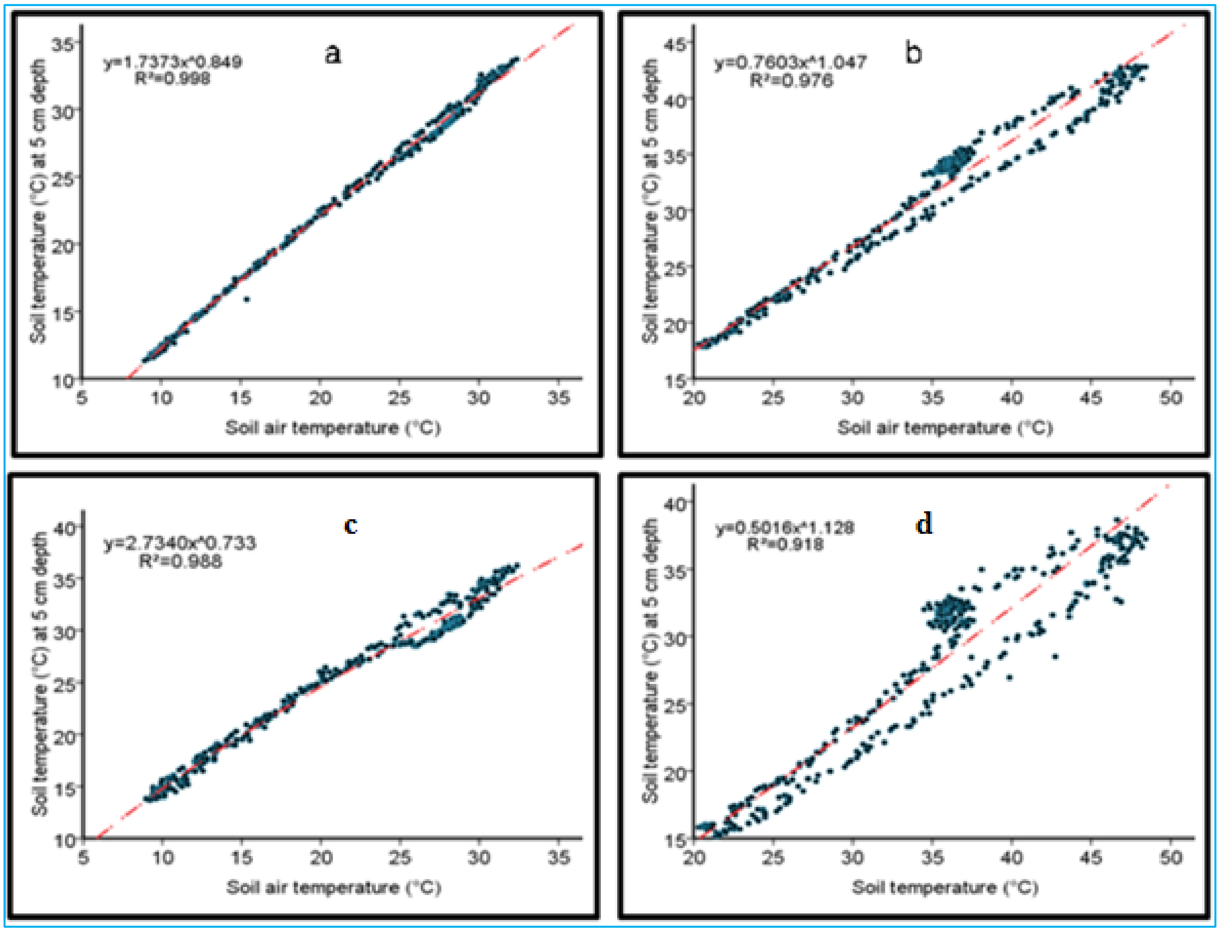
Figs. 5(a-f). Best-fit regression models (power except for 5.b and e that are exponential) for prediction of weekly soil temperature with air temperature in morning (a, c and e) and afternoon (b, d and f) at 5, 10 and 20 cm depths

temperature at the 5 cm soil depth, with the best fitted exponential model having an R^2 value of 0.990 [Fig. 4(b)]. Soil temperature prediction in the morning and afternoon at a 10 cm soil depth can be performed with a power best fit nonlinear model using the mean and maximum air temperatures, with R^2 values of 0.989 and 0.985, respectively [Figs. 4(c &d)]. Soil temperature prediction at a 20 cm soil depth can be performed with a power model using the mean air temperature in the morning and afternoon, with R^2 values of 0.986 and 0.987, respectively [Figs. 4(e&f)]. The weekly soil temperatures at 5, 10 and 20 cm soil depths were predicted via nonlinear regression analysis. Weekly morning soil temperature at a 5 cm soil depth can be predicted with a power model using the minimum air temperature, with an R^2 value of 0.989 [Fig. 5(a)]. However, for predicting the afternoon weekly soil temperature at the same depth, the exponential model was found to be the best by using the maximum air temperature, with an R^2 value of 0.991 [Fig. 5(b)]. The power model was found to best predict the weekly soil temperature at the 10 cm soil depth in the morning and afternoon using the mean and maximum air temperatures,



Figs. 6(a-f). Best-fit regression models (power except for 6.b which is exponential) for prediction of monthly soil temperature with air temperature in morning (a, c and e) and afternoon (b, d and f) at 5, 10 and 20 cm depths

with R^2 values of 0.990 and 0.987, respectively [Figs. 5(c&d)]. The mean air temperature was found to be most suitable for the exponential model for the prediction of weekly soil temperature in the morning at 20 cm, with an R^2 value of 0.971 [Fig. 5(e)]. Similarly, the mean air temperature was also found to be suitable for the power model for the prediction of afternoon weekly soil temperature at a depth of 20 cm, with an R^2 value of 0.986 [Fig. 5(f)]. Monthly soil temperature data, simulated based on the air temperature, are drawn by the use of models such as CENTURY (Parton, 1996), RothC (Colemon and Jenkison, 1996) and DNDC (Li, 1996). Site-specific calibration and validation of these models are necessary for the development of new regression models. Hence, for the monthly soil temperature prediction, regression analysis was performed, and the best fit regression models are shown in Figs. 6(a-f). The minimum air temperature was found to be most suitable for the prediction of the monthly morning soil temperature at 5 and 10 cm soil depths [Figs. 6(a&c)] and the maximum air temperature was found to be good for predicting the afternoon soil temperature at the same depths [Figs. 6(b&d)]. The power and exponential models were found to be the best-fit models for morning and afternoon soil temperature



Figs. 7(a-d). Best-fit regression models (power) for prediction of daily soil temperature with surface soil (5 cm depth) temperature in morning (a and c) and afternoon (b and d) at 10 and 20 cm depths

prediction, with an R^2 value of 0.991 in both models at a 5 cm soil depth [Figs. 6(a&b)]. The power model was found to be the best fit for the prediction of the monthly soil temperature at the 10 cm soil depth, with R^2 values of 0.977 and 0.990, respectively [Figs. 6(c&d)]. The mean air temperature was found to be most suitable for the prediction of the monthly soil temperature at a 20 cm soil depth with a power model, with an R^2 value of 0.993 in the morning as well as in the afternoon [Figs. 6(e&f)]. Regression analysis was used to predict the daily soil temperature at 10 and 20 cm soil depths with the morning and afternoon temperatures at the soil surface (5 cm depth). The results of the analysis are presented in Figs. 7(a-d). The power model was found to be the most suitable model for predicting the morning and afternoon daily soil temperatures at a 10 cm soil depth, with R^2 values of 0.998 and 0.976, respectively [Figs. 7(a&b)]. The power model was also found to be the best fit model for the prediction of daily soil temperature at a depth of 20 cm in the morning and afternoon, with R^2 values of 0.988 and 0.918, respectively [Figs. 7(c&d)]. Our findings for improving soil temperature by using various regression models at varying depths were supported by Barman *et al.*, (2017), who predicted the soil temperature at 5 and 10 cm soil depths in the alluvial soil of the lower Indo-Gangetic Plains in India. Soil temperature prediction at a 10 cm soil depth was also performed by Mampitiya*et al.*, (2024) in Nukus, Uzbekistan, using artificial intelligence. The models developed here for the prediction of soil temperature at various depths can be effectively used in the planning of agricultural practices,which can optimize the policy and management responses against the variability of soil physical, biological and chemical properties to ensure sustainable food production in the Upper Gangetic Plains of India.

4. Conclusions

Soil temperature plays a pivotal role in agricultural decision making.The key to attaining agricultural climate resilience in the event of its widespread unavailability is data-driven soil temperature prediction for a location. According to our research, the soil temperature in the upper Gangetic Plain region of India, increases up to 20 cm in the morning as soil depth increases, but falls with increasing soil depth in the afternoon. In conformity with the fluctuations in air temperature, there was notable daily, weekly, monthly and seasonal variation in soil temperature at various depths. The study also showed that by using best-fit empirical nonlinear regression power or exponential models, the morning and afternoon soil temperatures in the Upper Gangetic Plain's alluvial soils can be accurately predicted at daily, weekly, and monthly levels with minimum, maximum, or mean air temperatures. The accuracies ranged from 97.1 to 99.1%. We thus propose that soil temperature can be easily predicted from air temperature by using these identified models. Crop management planning and techniques can change the unwanted soil temperature. The data generated in this study can be used to evaluate how climate change is affecting agriculture and to mitigate those effects by implementing appropriate technologies. Higher agricultural productivity and profitability can be attained in comparable regions by implementing appropriate technologies based on soil temperature during the crop-growing season in cropping systems.

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Authors' Contributions

Dr. Tapendra Kumar Srivastav: Conceptualizing the research, designing the study.
Dr. Ram Ratan Verma : Collecting and analyzing data, designing the study and writing.
Dr. Pushpa Singh : Reviewing the work.
Mr. Raj Kumar Saroj: Collecting the data reviewing the work.

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