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Original Research Article

Effect of near-earth Surface Temperature on Soil Temperature at 5 cm depth

8 **ABSTRACT**

The research investigates the effects of ground surface temperature (air temperature) on soil temperature at a depth of 5 cm. The study covers a period of fourteen (14) months from May 2010 to June 2011 in Akure, Southwestern Nigeria. With the aid of an automatic weather station, temperature readings were taken at a depth of 5 cm below the soil surface at five (5) minute intervals daily. It was also observed that many analyses of soil temperature are based on the theories of heat flow and energy balance. The study reveals that surface temperature has a weak effect on soil temperature. The best correlation coefficient obtained for the study period is about 0.56 with a quadratic equation of order 2 at 5% significance level. This implies that air temperature cannot be solely used to predict soil temperature at a depth of 5 cm. A study of diurnal variation reveals that air temperature is usually higher than soil temperature during the day, and vice versa. The study also revealed that surface and soil temperatures are generally lower during the wet months when compared with the dry months. The wet season average daily temperatures are 23.42 °C and 27.69 °C for air and soil while the corresponding dry season values are 33.92 °C and 30.91 °C respectively. The results are recommended for agricultural purposes such as determination of soil and environmental conditions for crop production.

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10 *Keyword: Heat flow, Energy balance, Surface temperature*

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12 **1.0 INTRODUCTION**

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14 The concept of temperature is rooted in the quantitative ideas of hot and cold based on our sense of touch. A body or
15 system that feels hot usually has a higher temperature than a similar system that feels cold. Most properties of matter
16 that can be measured depend on temperature. This is because temperature reveals microscopic information about
17 matter at any given time [1]. For instance, temperature is directly related to the average translational kinetic energies
18 of the molecules of a material. Hence, the temperature of a system contributes to the magnitude of thermal and
19 mechanical vibrations of a system.

20 Ground surface temperature is the measure of the average kinetic energy of the air molecules above the
21 ground surface, while soil temperature is the measure of the average kinetic energy of the air molecules below the
22 surface. Soil temperature varies in response to the change in radiant thermal and latent energy exchange processes
23 that proceed through the soil surface. Soil temperature is an important agro-meteorological parameter. In general, the
24 flow of heat through the soil is critical to plant growth. Extreme levels of soil temperature as well as air affect plant life.
25 The availability of water content causes variation in soil temperatures. The microclimate of soil is well understood
26 through the study of heat flux. The ground surface gets heated more during the day by intense solar radiation than the
27 layers beneath, resulting in a temperature gradient between the surface and subsoil. Within the soil, this causes heat
28 to flow downward as a thermal wave, the amplitude of which changes with depth. Estimation of heat flux from the soil

29 temperature data can provide an understanding of the gain or loss of heat by the soil from the atmosphere. Many
30 previous studies have been conducted on similar issues such as soil temperature prediction, heat storage variations,
31 thermal diffusivity of the soil, and so on [2-6]. Climatic conditions on the earth's surface are in part a function of
32 varying physical position (elevation, latitude, and aspect) and the influence of large-scale meteorological forces such
33 as air and ocean currents. The density and architecture of plant canopies in natural systems are directly influenced by
34 climatic factors.

35 By contrast, for agricultural systems, it is the crop canopies that often influence the local microclimate. In both
36 instances, the soil plays an important role in affecting the climate near the surface. The properties of the surface soil
37 layer, including colour, water content, texture, and density, affect the partitioning of incident radiation and the amount
38 of energy used to evaporate water, warm the air above the ground, or warm the soil. The amount of thermal energy
39 that moves through an area of soil in a unit of time is the soil heat flux or heat flux density [2]. The ability of soil to
40 conduct heat determines how fast its temperature changes during a day or between seasons. Soil temperature is a
41 key factor affecting the rate of chemical and biological processes in the soil essential to plant growth. However, the
42 importance of soil heat flux in predicting the energy transfer process in the soil cannot be overemphasized. Soil heat
43 flux is important in micrometeorology because it effectively couples energy transfer processes at the surface with
44 energy transfer processes in the soil [7].

45 Several models have been introduced to predict soil temp at different depths. These models are location dependent
46 [8-11]. Hence, there is need to consistently measure directly and compare result with some available models for
47 climatic regions. It is important to note that formulation of these models was based on empirical measurement taken in
48 specific climatic zones. Researches have revealed that soil temp is influenced by several factors such as depth,
49 weather, climate, soil type e.t.c [12]. For instance, [13] reported a close correlation between air temperature and soil
50 temperature at depth of about 20 cm in spring at Nanchang.

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53 1.2 SURFACE ENERGY BALANCE AND SOIL HEAT FLUX

54 In micrometeorology, measurement of soil heat flux is often considered within the context of the surface energy
55 balance

$$56 \quad R_n - G = LE + H \quad (1)$$

57 where R_n is the net radiation, G is the soil heat flux density at the soil surface, and
58 LE and H are the latent and sensible heat flux densities, respectively. All terms in the equation above have units of J
59 $m^{-2} s^{-1}$ or $W m^{-2}$. Note that in the equation stated above, all fluxes away from the soil surface are defined as positive
60 except for R . The left side of the equation ($R - G$), represents the available energy, while the terms on the right side
61 (LE and H) are often referred to as the turbulent fluxes. Much of the energy that enters the soil during the day returns
62 to the atmosphere at night through terrestrial long-wave radiation. As a result, G is frequently the smallest component
63 of the daily surface energy balance and has been overlooked in some cases; however, there are often significant
64 transfers of energy into and out of a soil during both day and night hours, and failure to include G in short-time (i.e.,
65 hourly) energy balance determinations can lead to significant errors [14].

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67 2.0 METHODOLOGY

68 2.1 RESEARCH LOCATION AND INSTRUMENTATION

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70 The experimental site used in this study is the Meteorological Observatory Garden of the Department of Physics,
71 Federal University of Technology Akure (FUTA), shown in Figures 1 and 2. Surface and soil temperatures were
72 retrieved from the archive of the automatic weather station. The weather station is a Davis Vantage Pro Instrument
73 with multiple sensors for measuring such as temperature, humidity, pressure, wind speed, wind direction. It has a
74 resolution of 5 minutes and it is integrated with a data logger for the data measured at every time interval.

75 The data acquired from the automatic weather station covers the two major seasons in Nigeria, which are the rainy
76 and dry seasons. The atmospheric and soil temperatures (in degrees Celsius) cover a period of one year from May
77 2010 to June 2011. Surface temperatures utilized in this research refer to the air temperature at a height of 200 cm
78 above the surface of the ground. The soil temperature is the temperature of the soil as measured by a temperature
79 sensor buried at a depth of 5 cm below the soil surface. This depth was chosen because most soil ecosystem
80 processes such as decomposition of soil organic matter and mineralization of soil nutrients occur between 0 – 20 cm
81 below the top layers of soil [15-16].

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Fig. 1: The Automatic Weather Station at FUTA within the premises of Physics Department.



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Fig. 2: The Data Logger showing the process of data retrieval.

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2.2 COMPUTATION OF MEAN TEMPEARTURES

The 5-minute interval temperature data was downloaded to a computer and processed as follows. The data was sorted and arranged orderly by removing the null and obviously arbitrary values. The raw data was sorted into days and months to study the diurnal and seasonal variation of both temperatures. The average hourly values x for surface and soil temperatures were computed separately using equation (2).

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$$x = \frac{1}{n} \sum (P_1 + P_2 + P_3 + \dots + P_n) \tag{2}$$

100 where n is the number of datapoints and P_n is the temperature values at a 5 minute interval.

101 The corresponding daily values y for the entire study period were deduced by averaging the daily values as illustrated
102 by equation (3)

$$y = \frac{1}{m} \sum x_1 + x_2 + x_3 + \dots + x_m \tag{3}$$

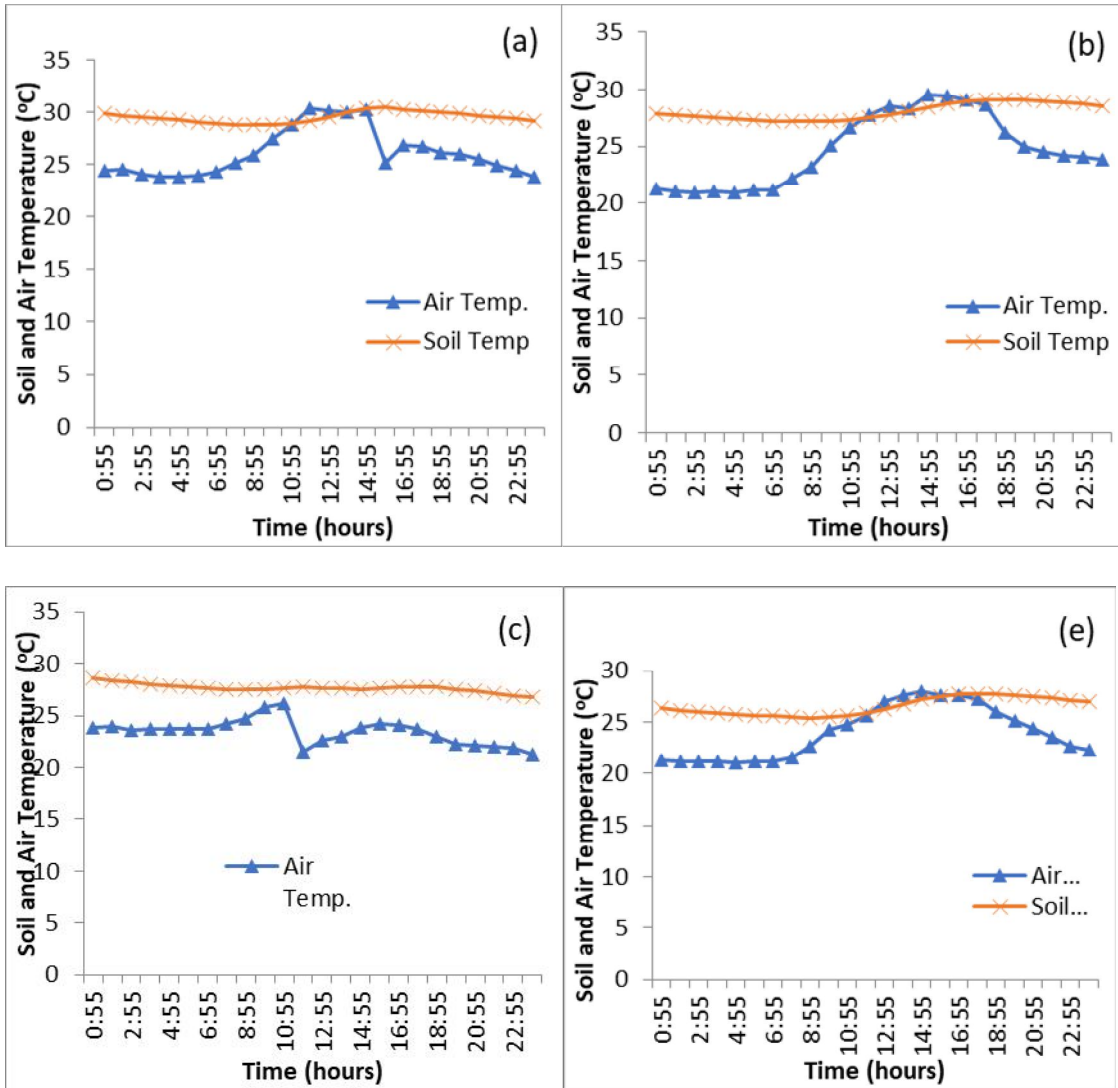
104 where m is the number of hours in a day (24) and x is the hourly mean values of the surface and soil temperature as
105 indicated in equation (2).

106 The maximum and minimum surface temperatures corresponding to the soil temperature were also determined from
107 the data. The diurnal, seasonal variation, and relationship between surface temperature and soil temperature were
108 investigated and discussed in the subsequent sections.

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110 3.0 RESULTS AND DISCUSSION

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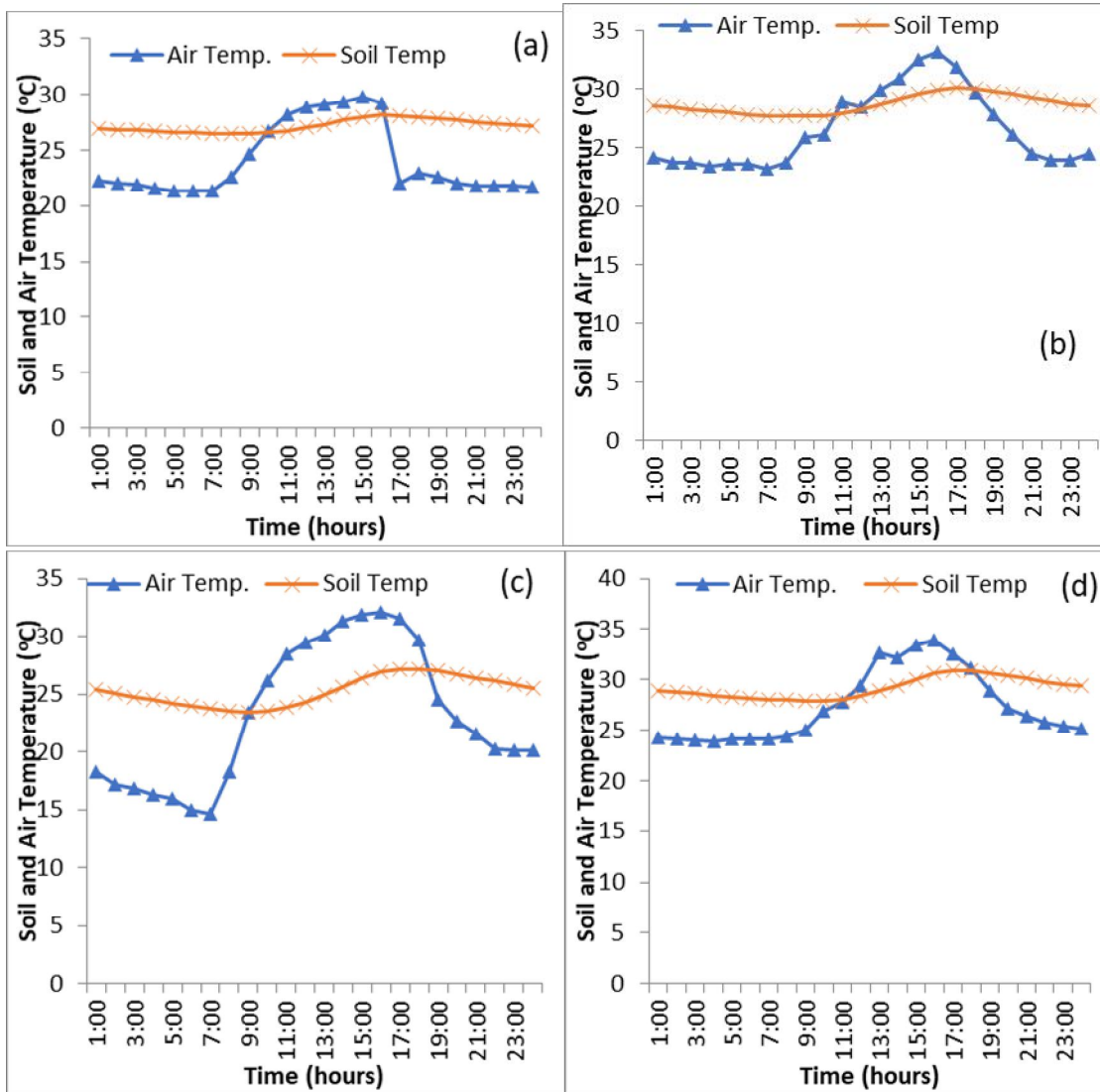
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116 Figure 3a-d: Diurnal variation of soil and air temperature during the wet months; (a) May, (b) June, (c) July, (d) August

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122 Figure 4a-d: Diurnal variation of soil and air temperature during the dry months; (a) November, (b) December, (c)

123 January, (d) February

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3.1 DIURNAL VARIATION

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The diurnal variation of air and soil temperatures was also studied based on the available data. Figures 3a-d and 4a-d show the diurnal variation for the wet and dry months. It was observed that both air and soil temperatures are usually low during the early hours of the day, i.e., between 00:00 and 10:00 hours. This could be attributed to the absence of solar radiation from the sun. The gradual increase in atmospheric temperature during the day is mostly due to the convective heating of matter by solar radiation [17]. The quantity of heat energy absorbed by the soil depends on the mass of soil exposed to the sun and other factors, such as the specific heat capacity of the soil. The consequence is an increase in temperature with depth, which is a unique feature of the troposphere [18]. This explains why the measured soil temperature is always higher than the corresponding air temperature.

As the sun rises, both the air and soil temperatures rise gradually with respect to the radiant energy emitted by the sun per unit time.

Both temperatures increase gradually until they attain peak values. Figures 3 and 4 indicate that the average daily temperatures for both air and surface attain peak values between 14:00 and 16:00, which implies that maximum solar radiation is received by the soil during this period. The maximum daily air and soil temperatures throughout the study period are 33.92 °C and 30.91°C which were recorded at about 16:00 in February, respectively. It is worthy to note that the air temperature gradually surpasses the soil temperature during that period of the days. This is due to the direct and ground-reflected heat fluxes received by the air molecules near the soil surface. This is the period when the

142 air temperature reaches its daily maximum, as shown in figures 3 and 4. Similar results were obtained by [19] for soil
143 temperatures between 0 – 20 cm. The temperature begins to fall due to the gradual disappearance of solar radiation.
144 The air molecules near the surface lose heat at a higher rate than the soil; hence, its temperature becomes lower than
145 that of the soil.

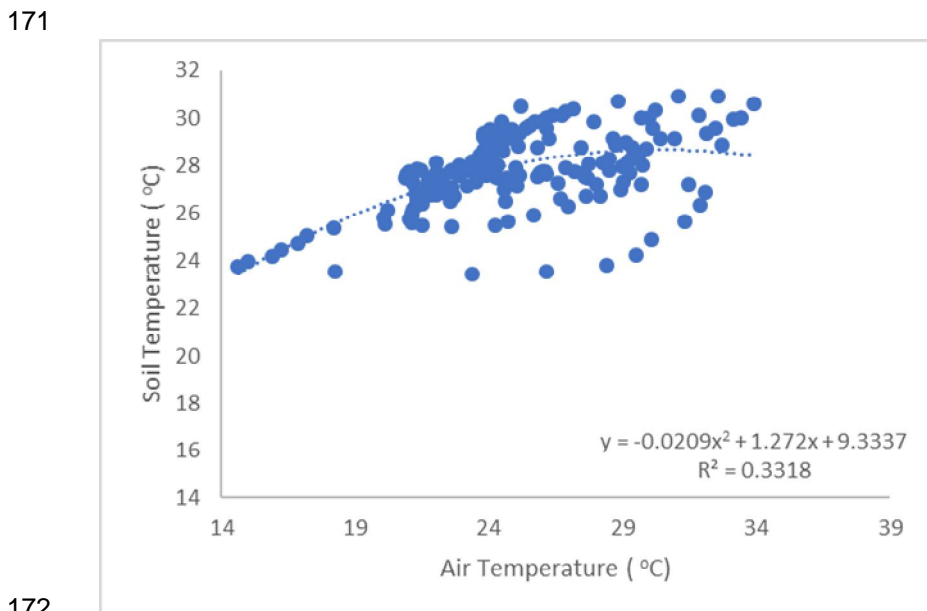
147 3.2 SEASONAL VARIATION OF AIR AND SOIL TEMPERATURE

148 The seasonal variation of air and surface temperature was studied by considering the months where the seasonal
149 effects on temperature were intense. The selected wet season months are May, June, July, and August, while the dry
150 months are November, December, January, and February. In the wet months, the air temperature varies between
151 21.5 °C in July and 30.4 °C in May, while the soil temperature is fairly constant between 29.8 °C and 26.0 °C. This
152 shows that the temperature is uniform throughout the rainy season. This could be attributed to frequent rainfall, which
153 keeps the soil moisture content at a minimal during this period. Figures 3a-d show that air temperature rises slightly
154 between 11:00 a.m. and 15:00 a.m. due to sporadic solar activity during the rainy season. The influence of solar
155 radiation during the rainy season is quite minimal when compared with the dry season. The 'bumpy' shape of the
156 hourly trend of the air temperature is more pronounced in the dry season, as depicted in figures 4a-d. This is because
157 the air temperature rises sharply as a result of intense solar radiation between 9:00 hrs and 15:00 hrs daily. This
158 causes the air temperature to surpass the soil temperature during the active solar hours. The maximum and minimum
159 daily air temperatures were observed to be about 33.92 °C in the month of February and 14.60 °C in January during
160 the dry season, respectively. The extremely low air temperature in January could be likened to the peak of harmattan
161 when cool winds from the Sahara Desert move into the Gulf of Guinea [20]. Hence, the super-cooled wind suppresses
162 the air temperature. This is usually accompanied by hot weather between February and March signifying the end of
163 dry season.

165 3.3 CORRELATION BETWEEN SOIL AND AIR TEMPERATURE

166 The two temperatures were compared to investigate the relationship between them. A scatter plot of soil temperature
167 against air temperature for all the periods of the days shown in Figure 5 reveals that there is a very poor correlation
168 between these temperatures. Among all the regression models, a polynomial of order 2 produces the best correlation
169 coefficient of 0.33.

$$170 S_t = -0.0209A_t^2 + 1.272A_t + 9.3337 \quad (4)$$

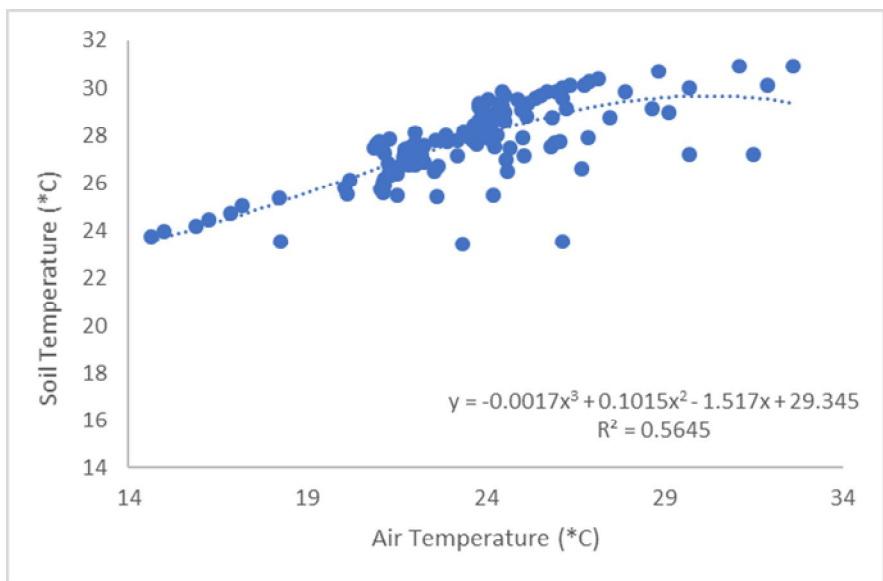


172 Figure 5: Correlation between air and surface temperature for inactive and active solar periods

175 This implies that equation (4) cannot satisfactorily predict the soil temperature for a known air temperature. In order to
176 obtain a better result, the active solar hours of 10:00–17:00 hours were filtered, since Figures 3a-d and 4a-d had
177 earlier depicted a poor relationship during the sunshine hours. The new scatter plot and the corresponding equation
178 obtained are presented in figure 6 and equation (5) respectively. Although the correlation coefficient improved to

179 about 0.56, this is not sufficient to recommend the modelled equation for prediction of soil temperature based on air
 180 temperature. The improved relationship is due to the absence of solar radiation which creates tendency for the ground
 181 surface air molecules and the soil to approach thermal equilibrium.

$$S_T = -0.0017A_T^2 + 0.1015A_T + 29.345 \quad (5)$$



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 186 Figure 6: Correlation between air and surface temperature for inactive solar period

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 188 The correlation results obtained in this study were compared with previous works as presented in Table 1. Although
 189 the results from most of the previous work depicts good correlation, factors such as climate, soil type could have
 190 influenced the results. Nigeria (Akure) is a tropical climatic region whereas the stations used in the available previous
 191 are temperate except South Africa which is subtropical. Moreover, the type of soil used most previous studies were
 192 not indicated. In order to obtain consistent, effective and reliable comparative analysis, factors that influence soil
 193 temperature such as soil depth, soil type and climate should be made uniform.

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 195 Table 1: Comparison of correlation coefficient from previous and present studies

| Literature | Soil Depth (cm) | Location | Climate | Correlation coefficient (R ²) |
|---|-----------------|----------------------|-------------|---|
| Zheng <i>et. al.</i> , 1993 [8] | 10 | United States | Temperate | 0.86 |
| Ana <i>et. al.</i> , 2000 [21] | 0 | South Africa | Subtropical | 0.996 |
| Ahmad and Rasul 2008 [9] | 10-20 | Faisalamad, Pakistan | Temperate | 0.32 – 0.86 |
| Zhan 2019 [13] | 20 | Nanchang, China | Temperate | 0.85 |
| Present study (Lawal <i>et. al.</i> , 2022) | 5 | Akure, Nigeria | Tropical | 0.33 - 0.56 |

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 198 **4.0CONCLUSION**
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200 The effects of surface temperature on soil temperature have been investigated, using Akure as the study location. The
 201 diurnal variation reveals that soil temperature is typically lower than air temperature, but this trend is reversed during
 202 peak solar hours due to direct and ground-reflected heat flux absorbed by air molecules. It was observed that the
 203 values of surface or air temperatures are high in the dry season and apparently low in the rainy season. This is in
 204 conjunction with the associated temperatures in the tropical region. It was also observed that many analyses of soil
 205 temperature are based on the theories of heat flow and energy balance. Although some similar research works
 206 conducted in other climatic regions suggest good correlation between air and soil temperature, the present study

207 reveals the existence of a very weak coefficient of correlation between these temperatures. This is attributed to the
208 impact of other determinants of soil temperature such as soil depth, soil type, climate etc. The results suggest that the
209 variation of air temperature is not absolutely governed by soil temperature.

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