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DEVELOPMENT OF SOIL PROFILE TEMPERATURE PREDICTION MODELS FOR BARE AND SOLARIZED FIELD CONDITIONS

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Abstract: Soil solarization is a simple and effective technique for controlling problems like weeds and soil borne pathogens by means of increasing moist soil temperature through trapping heat by using the thin transparent polyethylene sheet for few weeks. The soil temperature models 'SOILTEMP' were developed to predict the diurnal variation of soil profile temperature at various depths for solarized (mulch covered) and bare soil by incorporating different types of input data. The accuracy of models was evaluated using model efficiency coefficient (*E*). Except for bare soil at 15 cm depth, positive values of *E* were obtained whereas at 15 cm depth for bare soil negative *E* values of *E* were observed. The highest *E*=0.92 was obtained at 5 cm depth for solarized soil and weekly average data whereas lowest one (*E*= 0.39) obtained at 10 cm depth for bare soil and biweekly data. The developed models will be useful to predict the soil profile temperature and to study the effect of various input parameters to achieve desired effect of soil solarization without conducting the experiments and thereby to save cost and time.

Key words: *soil solarization, soil profile temperature, energy balance equations, mathematical models, model efficiency.*

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INTRODUCTION

Soil solarization, involves the use of sun heat as a lethal agent for pest and weed control through the use of transparent thin (25 micron) polyethylene sheet for capturing the solar energy, has potential advantages. It is non-chemical method hence not hazardous to the user and does not involve substances toxic either to consumer or host plant or other organisms. Soil temperature also has direct effect on biological process like seed germination, seeding emergence and growth, root development, nutrient and water uptake and the microbial activity. Further, it is less expensive than other methods and easy to implement in large or small areas.

Soil temperature prediction simulation models are very useful to the users to predict the soil profile temperature under solarized and non-solarized conditions using the various weather, soil and polyethylene mulch input parameters which could save cost and time for conducting the experiment. Many researchers [1,5,6,8] studied the soil profile temperature characteristics for bared and solarized conditions and its benefits. The soil was covered with transparent plastic sheeting prior to planting increased the soil temperature 5cm below the surface by 12°C. They found that 40°C could be maintained for 119 hours under solarized condition whereas for uncovered control plot it could never achieved. The highest and lowest temperatures were found to be 51° and 27°, respectively, for covered soil and 39° and 23°, respectively, for the control plot [9]. The Maximum temperature in upper soil layers under ideal conditions was achieved within 3-4 days after solarization. Typical maximum soil temperature in solarization plots was 8-12 °C higher than the corresponding non-solarized plots [4].

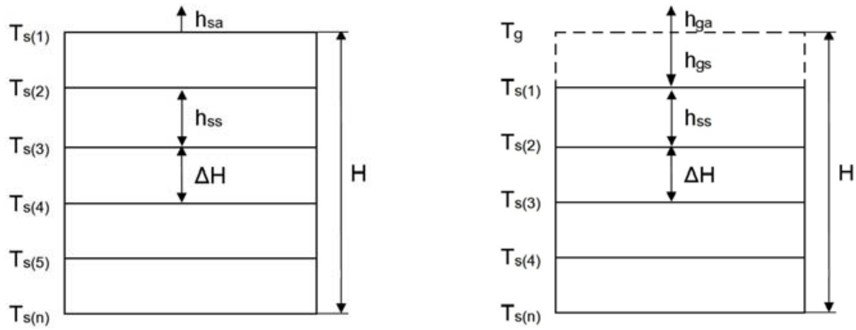
The soil temperature simulation models 'SOILTEMP' were developed to predict the soil profile temperature at various depths and different time interval under solarized (mulch covered) and non-solarized (bare) conditions. The models can be used to study the effect of weather parameters, soil properties and mulch properties on soil profile temperature.

MATERIAL AND METHODS

Theoretical Analysis

Fig. 1 shows the various heat transfer coefficients occurring at different components of the soil profile system considered for the study i.e. at transparent glazing, soil surface and subsequent layers of the soil profile. The mathematical models were developed by writing the energy balance equations for different components of the soil solarization system and solving it by adopting the finite difference technique. The computer program in FORTRAN language was prepared to obtain predicted results. The following assumptions were made for the development of mathematical models.

1. There is no heat loss perpendicular to the direction of flow of heat in the soil.
2. The heat flows in the soil profile among soil particles through conduction only.
3. The properties of plastic sheet and soil profile remains unchanged with time lapse.
4. The soil bed consists of number of thin layers stacked upon each other.



a. Uncovered *b. Covered*

Figure 1. Schematic view of the soil profile temperature prediction system for uncovered (a) and transparent polyethylene covered (b) conditions

Energy Balance Equations

1. Uncovered soil

For surface layer

$$\Delta H\ \rho_s C_s(1-\varepsilon)\ dT_{s(1)}/dt = \alpha_s I - h_{as}(T_{s(1)}-T_a) - K_s/\Delta H\ (T_{s(1)}-T_{s(2)}) \quad (1)$$

Where:

ΔH	[m]	- spacing between two successive soil layers,
H	[m]	- depth of soil bed,
ρ	[kg·m^{-3}]	- density,
C	[J·kg^{-1}°C^{-1}]	- specific heat,
ε	[-]	- porosity, decimal,
T	[°C]	- temperature,
t	[sec]	- time,
α	[-]	- solar absorbance,
I	[W·m^{-2}]	- solar flux,
h	[W·m^{-2}°C^{-1}]	- heat transfer coefficient,
K	[W·m^{-1}°C^{-1}]	- thermal conductivity,

For subsequent layers (I=2,n)

$$\Delta H\ \rho_s C_s(1-\varepsilon)\ dT_{s(1)}/dt = h_{ss}(T_{s(I-1)}-2T_{s(I)}+T_s(I+1)) \quad (2)$$

2. Covered soil

For glazing

$$M_g C_g dT_g/dt = \alpha_g I + h_{sg}(T_{s(1)}-T_g) - h_{ga}(T_g-T_a) \quad (3)$$

Where:

M [kg·m^{-2}] - mass,

For surface layer of soil

$$\Delta H\ \rho_s C_s(1-\varepsilon)\ dT_s(1)/dt = \tau_g \alpha_s I - h_{sg}(T_{s(1)}-T_g) - h_{ss}(T_{s(1)}-T_{s(2)}) \quad (4)$$

For subsequent layers of soil (I=2,n)

$$\Delta H\ \rho_s C_s(1-\varepsilon)\ dT_{s(I)}/dt=h_{ss}(T_{s(I-1)}-2T_{s(I)}+T_s(I+1)) \quad (5)$$

3. Boundary conditions

$T_g(0) = T_s(1)$, and
$T_s(H,0) = T_a(1)$

Heat Transfer Coefficients

The various heat transfer coefficients i.e. radiative and wind related convective heat transfer coefficients, h_{ga} and h_{as}; the radiative and natural convective heat transfer coefficient, h_{sg} and the conductive heat transfer coefficients between soil particles, h_{ss} were calculated by using the standard heat transfer relations given by [2].

Input Parameters

For the numerical calculations, weather parameters i.e. solar radiation and ambient temperature and properties of soil were measured whereas the properties of polyethylene mulch were obtained from the manufacturer's catalog and literature.

Weather Data: The daily hourly variation in ambient air temperature (T_a) and solar flux during the experimental period (11-25 May) at Junagadh (21.52° N, 70.47° E), Gujarat, India were measured by using copper constant *K*-type thermocouple wire sensor and pyranometer sensors attached with the computerized DT-600 Data-Taker data logger. The hourly average data for typical day (19th May), weekly average (11-18 May) and biweekly i.e. 15 days average (11-25 May) are presented in Fig.2.

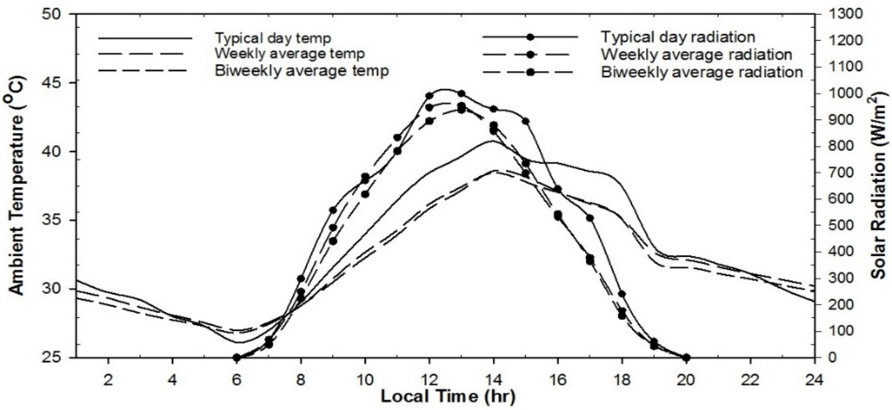


Figure 2. Average hourly weather data for the month of May in Junagadh.

Physical properties of soil: The soil samples from three locations of each experimental plots were drawn by using the core-cutter just before covering of plastic sheet and just after removal of the *PE* sheet. The samples were analyzed for evaluating the physical properties i.e. moisture content, bulk density, particle density, and porosity.

The moisture content of soil samples was determined using the hot air oven method. The bulk density of soil was calculated on the basis of weight of the sample and volume of core cutter. Particle density was determined by using picnometer method. Based on bulk and particle density the porosity of soil samples was calculated. The relationship between bulk density, porosity and moisture content and porosity was established to incorporate into the model.

Optical and thermal properties of soil: The values of optical properties of the soil i.e. absorbtivity (α_s) and emissivity (ε_s) were considered as 0.7 and 0.9 respectively. The thermal properties i.e. specific heat and thermal conductivity of soil were computed by using the following relationships.

Specific heat

$$C_{soil} = f_m\, C_m + f_o\, C_o + f_w\, C_w \tag{6}$$

Where:
$f_m = (1\text{-}\varepsilon)\, x$ - mineral content in solids
$f_o = (1\text{-}\ \varepsilon)\, x$ - organic matter content in solids

Thermal Conductivity

$$K_s = A + B\theta - (A\text{-}D)\, exp[-(C\theta)^E] \tag{7}$$

Where:
θ [-] - moisture content,
τ [-] - solar transmittance,
V [-] - volumetric fraction,
f [-] - fraction,
A, B, C, D and *E* are constants. The constants are calculated as follows:
$A = 0.65 - 0.78\, \rho_{soil} + 0.6\, \rho_{soil}^2$
$B = 2.8\, V_s\, \theta$
$C = 1.0 + 2.6 f_{cl}^{-1/2}$
$D = 0.03 + 0.7V_s^2$
$E = 4.0$

Properties of mulch cover: Various properties of 25 micron polyethylene sheet i.e. bulk density, specific heat, solar radiation absorbtivity, transmissivity and emissivity were obtained from manufacturer catalog. These were considered as $\rho_s = 920$ kg·m^{-3}, $C_s = 2300$ J·kg^{-1}°C^{-1}, $\alpha_{tg} = 0.05$, $\alpha_{bg} = 0.9$, $\tau_{tg} = 0.85$, $\tau_{bg} = 0.85$, $E_g = 0.9$, respectively.

Experimental Details and Soil Profile Temperature Measurements

The soil and farmyard manure (*FYM*) were sieved to reject pebbles and debris and three beds of size 2.5 x 10 m were prepared. The beds were filled up to 20 cm depth with soil and *FYM* mixture (6:1 soil and *FYM*). These soil beds were moistened with help of shower and kept for overnight. Next day early morning clear transparent polyethylene sheets of 25 microns thickness were used to cover the beds. All the edges were buried in soil and compacted to prevent heat and soil moisture loss. First plot was kept uncovered considered as control while second plot was covered with 25 micron transparent polyethylene sheet for 15 days and third plot was covered for 30 days during the month of May at nursery of the department of Renewable Energy & Rural Engineering, Junagadh Agricultural University, Junagadh, Gujarat, India. Based on earlier study effect of 15 days solarization duration was found at par with 30 days duration at given location hence, in this study, input data of typical day, weekly average and biweekly average (15 days) were considered for the development of models. The hourly temperatures of soil profile at 5, 10 and 15 cm depths were recorded by using the *RTD* temperature sensors attached with data logger. The temperature characteristics i.e. diurnal variation of soil profile temperature for bare soil (uncovered) and transparent polyethylene mulch conditions have been studied.

Verification of Models and Efficiency

By using the developed mathematical models, the soil profile temperatures at respective depths were predicted and plotted against the time for uncovered and solarized conditions. The theoretical results were compared with experimental results to simulate the model.The efficiency of the developed mathematical models was calculated using model efficiency coefficient as given below (Nash and Sutcliffe,1970) [7]:

$$E = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - \overline{X}_i)^2} \tag{8}$$

Where:

X [-] - observed data,

$\bar{X}$ [-] - mean of observed data,

Y [-] - predicted data.

RESULTS AND DISCUSSION

Effect of Moisture Content on Physical and Thermal Properties of Soil

The average moisture content on wet basis and bulk density of soil samples from control plot before covering and after removal of plastic sheet were found to be 26.55%, 1456 kg·m^{-3} and 19.22%, 1347kg·m^{-3} respectively whereas for 15 days soil solarization treatment plot, the similar observations were observed as 24.11%, 1450 kg·m^{-3} and 21.38% 1406 kg·m^{-3} respectively.

Table: 1 Relationship of moisture content and physical and thermal properties soil

Property	Relationship			
	Control	R^2	15 days	R^2
ρ_{soil}	$14.54\theta+1070.2$	1.0	$14.457\theta+1097.3$	1.0
ε	$58.964-0.5577\theta$	1.0	$57.343-0.5626\theta$	1.0
C_{soil}	$31.694\theta+1090.5$	1.0	$31.7\theta+1093.5$	1.0
K_{soil}	$0.2243 - 0.0351\theta + 0.0057\theta^2 - 0.000009\theta^3$	0.99	$0.2298-0.0338\theta+ 0.0056\theta^2 - 0.00009\theta^3$	0.99

The particle density of the above plots soil were found to be 2608 and 2572 $kg \cdot m^{-3}$ respectively. The relationship between moisture content and various physical and thermal properties are given in Tab. 1.

The porosity of the respective plot soil before and after soil solarization was found as 44.15%, 43.78%, and 48.25%, 45.31% respectively. The average specific heat and thermal conductivity of the soil samples of the above plots were calculated as 1816, 1814 $J \cdot kg^{-1} {}^{\circ}C^{-1}$ and, 1.32, 1.31 $W \cdot m^{-1} {}^{\circ}C^{-1}$ respectively.

Soil Profile Temperature Characteristics

The temperature characteristics of control (uncovered) and 15 days solarized (covered) soils for typical day (19th May) weekly average and biweekly average are presented in Fig. 3.

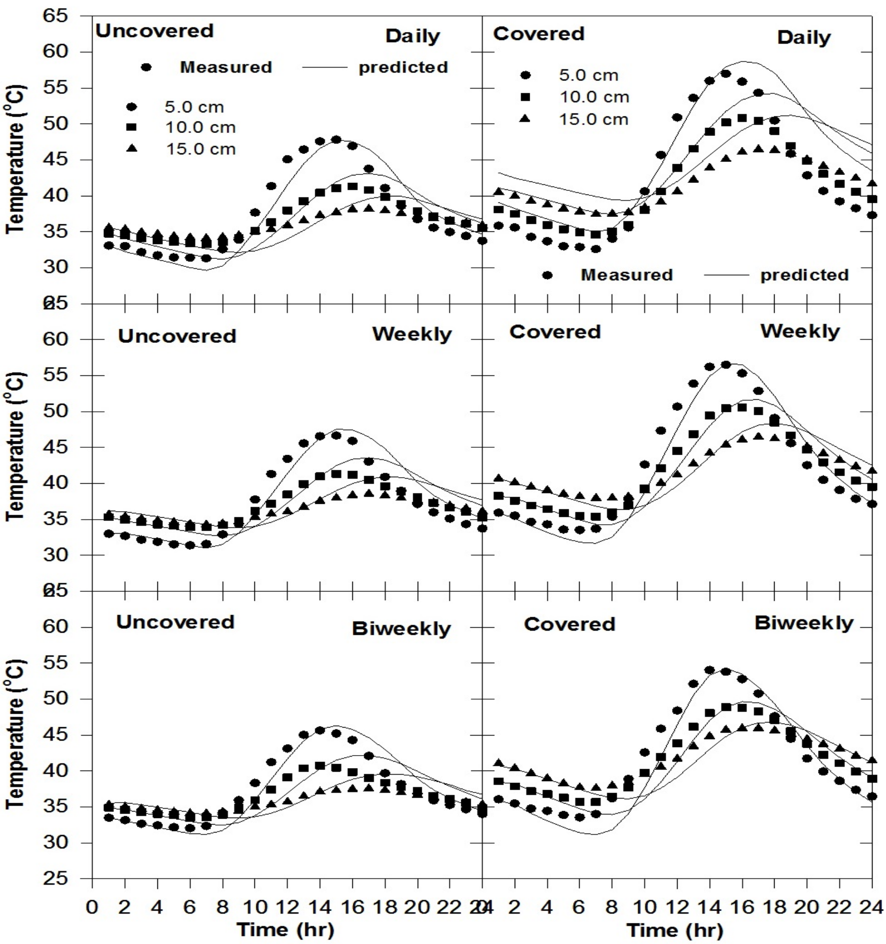


Figure 3. Measured and predicted soil profile temperature at different depths for covered and uncovered soil

The result shows that for both uncovered and covered soils, for 5 cm depth, temperatures were decreased steadily till 7.00 hour and then increased rapidly till 15.00-16.00 hours and again decreased for the remaining hours.

The similar trends were also observed for 10 and 15cm depths. However, with increase in depth, rise and fall of soil layer temperature was delayed by 1-2 hours as compared to its previous layer. The figures also show reverse trend during off-sunshine hours as that of sunshine hours. The results on temperature characteristics showed that the maximum temperatures of uncovered soil at 5.0, 10.0 and 15.0 cm depth on typical day were found to be 47.78°C, 41.31°C and 38.17°C respectively whereas the minimum temperatures at given depths 31.29°C, 33.28°C and 34.10°C respectively. The increment in maximum and minimum soil temperatures due to solarization (covering) at corresponding depths on typical day were found as 9.18°C, 9.54°C, 8.28°C and 1.28°C, 1.34°C, 3.35°C respectively. The similar trends were also observed for hourly variation in weekly and biweekly soil profile temperatures. The predicted soil profile temperature data obtained by using the mathematical model were fitted to the experimental data. A good agreement between experimental and predicted data was observed.

Verification and Efficiency of Models

The predicted data on hourly variation in soil profile temperature for typical day, weekly average and biweekly average obtained by using the mathematical models for uncovered and covered soils are plotted against experimental data (Fig. 3) to compare predicted and experimental results. From figures it can be seen that theoretical results have followed the similar pattern that of experimental results have. Thus, a good agreement with experimental data is obtained at all depths for different sets of input data. The effect of types of input data, depth of profile and solarization treatment on efficiency coefficient (*E*) for is presented in Tab. 2. From table it can be seen that for bare soil, values of E are very close to 1.0 at 5.0 cm depth followed by at 10.0 cm depth whereas at 15.0 cm depth negative values are obtained for all three types of input data.

Table 2. Model efficiency coefficient (E) for different sets of conditions

Sr. No.	*Type of input data*	*Bare field (control)*			*Solarized (mulch covered)*		
		5 cm	*10 cm*	*15 cm*	*5 cm*	*10 cm*	*15 cm*
1	*Typical day*	*0.88*	*0.59*	*-0.36*	*0.82*	*0.74*	*0.53*
2	*Weekly average*	*0.87*	*0.45*	*-0.12*	*0.92*	*0.90*	*0.78*
3	*Biweekly average*	*0.87*	*0.39*	*-0.41*	*0.90*	*0.86*	*0.75*

However, in case of solarization treatment, *E* values at 15 cm depth are found positive which indicates except for 15 cm bare soil, predicted hourly soil profile temperature data are in good match with experimental data and accuracy of the models is quite good whereas negative values indicates observed mean is a better predictor than the model. Values of *E* (except 15 cm depth) for bare soil varied between 0.87 and 0.39 whereas for soil soilarization treatment these values ranged between 0.92 and 0.53. Thus, soil temperature prediction model gave better accuracy for solarization condition as compared to bare soil. The effect of types of data on accuracy of model shows that weekly average input data has better accuracy followed by biweekly and typical day data. It can also be seen that soil profile depth has prominent effect on E values as compared to covering and types of input data.

CONCLUSIONS

From the above discussion it may be concluded that the developed SOILTEMP models can be effectively used to predict diurnal variation of soil profile temperatures at different soil profile depths for bare field (except for 15 cm depth) and solarized conditions using weather data of the location, physical, thermal and optical properties of the soil profile and mulch material. The accuracy of the models is significantly influenced by soil profile depth and mulch condition whereas types of data has little impact on accuracy of the developed models.

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Subscripts nomenclature

a ambient
g glazing
ga glazing-ambient
gs glazing-soil
(I)/i ith layer
cl clay fraction
m mineral
o organic matter

s soil/solid matter
sg soil-glazing
ss soil-soil
t transparent
(1) first layer

RAZVOJ MODELA ZA PREDVIĐANJE TEMPERATURE ZEMLJIŠNIH PROFILA U OGOLJENIM I OSUNČANIM POLJSKIM USLOVIMA

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Sažetak: Osunčanje zemljišta je jednostavna i efikasna tehnika za kontrolu problema kao što su korovi i patogeni koji nastaju u zemljištu, povećavanjem temperature vlažnog zemljišta zadržavanjem toplote tankom providnom polietilenskom folijom na nekoliko sedmica. Modeli zemljišne temperature "SOILTEMP" su razvijeni da bi se predvidele dnevne varijacije temperature zemljišnog profila na različitim dubinama za osunčano (pokriveno malčom) i ogoljeno zemljište uključivanjem različitih ulaznih podataka. Tačnost modela je ocenjivana upotrebom koeficijenta efikasnosti modela (*E*). Izuzev ogoljenog zemljišta na dubini od 15 cm, gde je dobijena negativna vrednost koeficijenta *E*, u ostalim slučajevima su dobijene pozitivne vrednosti. Najviša vrednost *E*=0.92 je postignuta na dubini od 5 cm na osunčanom zemljištu sa sedmičnim srednjim vrednostima, gde je najniža (*E*= 0.39) dobijena na dubini od 10 cm za ogoljeno zemljište i dvonedeljne podatke. Razvijeni modeli će biti korisni za predviđanje temperature zemljišnog profila i proučavanje uticaja različitih ulaznih parametara radi postizanja željenog efekta osunčanja zemljišta bez izvođenja ogleda, što smanjuje troškove i štedi vreme.

Ključne reči*: osunčanje zemljišta, temperature zemljišnog profila, jednačine bilansa energije, matematički modeli, efikasnost modela.*

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