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Performance evaluation of different soil infiltration models under the long-term conservation agriculture based management practices

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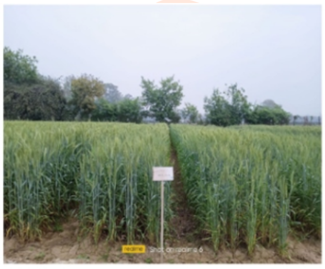
Abstract

Aim: This study aimed to assess the long-term impacts of various conservation agriculture practices on the infiltration characteristics of soil and to evaluate effectiveness of Kostiakov, Green and Ampt, and Philip models in predicting the infiltration rates.

Methodology: The treatments examined included the permanent broad bed (PBB), PBB with residue (PBB+R), permanent narrow bed (PNB), PNB with residue (PNB+R), zero tillage (ZT), and ZT with residue (ZT+R) and conventional tillage (CT). Infiltration models were fitted to the experimental data and performance of each model was evaluated using statistical criteria.

Results: Initial infiltration rate was maximum in PBB+R, which was 111.5% higher than in conventional tillage CT (lowest). Cumulative infiltration across all the treatments followed in the order of: PBB+R had the highest, followed by PNB+R>ZT+R>PBB>PNB>ZT>CT. The CA–based management practices showed 31.4–85.2% higher observed steady state infiltration rate than CT. The model derived parameters like "a" value of Kostiakov, "i_c" of Green and Ampt and "S" of Philip were higher under PBB+R than CT by 138.6, 154.3 and 112.1%, respectively. Kostiakov model performed the best for predicting infiltration rates with the highest $R^2 \geq 0.92$ and the lowest errors (RMSE≤1.26 cm hr^{-1}, ARE≤0.76 cm hr^{-1} and MAE≤0.96 cm hr^{-1}).



Treatments: ZT+R, ZT, PBB+R, PBB, PNB+R, PNB, CT

- **Initial infiltration rate (cm hr^{-1})**
  PBB+R>PNB+R>ZT+R>PBB>PNB>ZT>CT
- **Steady state infiltration rate(cm hr^{-1})**
  PBB+R>PNB+R>ZT+R>PBB>ZT>PNB>CT
- **Cumulative infiltration (cm)**
  PBB+R>PNB+R>PBB>ZT+R>PNB>ZT>CT

Models	Kostiakov model		Green and Ampt model		Philip model	
	a (cm/hr)	b	i_c (cm ha^{-1})	B (cm^2 ha^{-1})	S (cm^2 $ha^{-0.5}$)	K (cm ha^{-1})

Interpretation: Therefore, it was proventhat the empirical Kostiakov model could effectively represent the infiltration process in soil.

Key words: Conventional tillage, Infiltration models, Kostiakov model, Permanent broad bed, Residue

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Introduction

Conventional farming involves the repeated practices like tilling, harrowing disking for seed bed preparation and management of weeds, which accelerates the breakdown of soil organic matter (SOM) and release of the nutrients. However, the use of heavy machinery and frequent tillage results in soil compaction, decreased pore space, restricted water infiltration and limited crop root growth, ultimately affecting the crop yields (Raj *et al.,* 2023). Moreover, tillage operationexposes the soil to erosion by water and wind, triggerstopsoil loss, reduces fertility, and inhibits plant growth. To counter these challenges, conservation agriculture (CA) is extensively recognized as an effective method. Conservation agriculture includes reduced tillage or zero-till practices, maintenance of a minimum 30% crop residue cover, and employs crop rotations with cover crops. CA enhances the soil properties and processes, improves climate regulation by carbon sequestration, decreases greenhouse gas emissions, improves water infiltration and increases water regulation and availability by improving the physical, chemical and biological characteristics of soils (Pathak *et al.,* 2017; Adak *et al.,* 2023).

Rapid water infiltration is vital in lessening erosion and enhancing water storage in semiarid and arid areas (Klik *et al.,* 2020). Infiltration is important for assessing effective rainfall, runoff, groundwater recharge, and designing soil and water conservation channels. A thorough understanding of infiltration is essential for agriculture water management, watershed management and, for designing hydraulic structures (Pramanik *et al.,* 2019; Ghosh *et al.,* 2020). Several factors that affect the soil water infiltration are vegetation cover and tillage practices, soil density, porosity, surface unevenness, SOM content, soil aggregate stability, and soil moisture levels (Amami *et al.,* 2021). Various models have been usedto estimate the infiltration and to assist in designing irrigation systems and water management strategies. These models can be categorized into three types: empirical models, semi-empirical models and physical models (Mahapatra *et al.,* 2020). Several infiltration models proposed by different Scientists include the "Green & Ampt model" (1911), "Kostiakov model" (1932), "Horton model" (1940), "Philip model" (1957), "Smith and Parlange model" (1978), and "Singh and Yu model" (1990).

The choice of a suitable infiltration model is subjected to the soil types and field conditions. Among the proposed models, Kostiakov, Philip, and Green & Amptmodels are frequently used due to their simplicity and ease of computation (Atta-Darkwa *et al.,* 2022). Kostiakov model is derived empirically, whereas the Green & Amptand Philip models are based on physical processes. Previous studies have evaluated various physical and empirical infiltration models under different conditions, there is limited research on behavior of soil infiltration and the performance of these models under different long-term CA–based practices (Thierfelder *et al*., 2009; Amami *et al*., 2021). Studies has been carried out to evaluate and model soil infiltration rate. But our study emphasizes the effect of long-term conservation agriculture (13year) and different bed system of farming on soil infiltration. How the residue retention and bed management practices are affecting the soil infiltration in long run that could be concluded from the study so this area of research has much potential over the conventional modelling of soil infiltration.The current study aimed to assess the effects of various long-term CA-based management practices on soil infiltration characteristics, and evaluate the performance of infiltration models under CA-based practices.

Materials and Methods

Study area and experimental setup: The research was carried out in a long-term CA experiment that has been ongoing since 2010. The study was conducted in maize–wheat cropping system located at the research farm (MB-14B) of the Indian Agricultural Research Institute (IARI) in New Delhi, India (28°35´N latitude and 77°12´E longitude). The climate of the study area is subtropical semi-arid, with hot, dry summers and cold, moist winters. Soil at the location is categorized as Typic Haplustept, and it has a sandy clay loam texture.

The experimental design employed seven treatments in a randomized complete block design with three replications. Seven treatments included, zero tillage (ZT), ZT with residue (ZT+R) permanent broad bed (PBB), PBB with residue(PBB+R), permanent narrow bed (PNB), PNB with residue (PNB+R), and conventional tillage (CT). During initial year, narrow and broad bed plots were preparedusing a ridge/bed maker and maintained as permanent structures in subsequent years. The CT plots underwent seasonal land preparation involving one pass each with a tractor-drawn disk plough, cultivator and harrow, followed by levelling to achieve a fine tilth. In contrast, no ploughing was conducted in the other plots. For residue removal (ZT, PPB and PNB) and CT plots, previous maize crops were manually harvested at base. In residue retention plots (ZT+R, PBB+R, and PNB+R), about 40% of previous crop straw/stover was kept as stubble. The details of field geometry for all the treatments, *i.e.,* bed and furrow width of PBB and PNB, and details of planting geometry of crops have been reported by Das *et al.* (2018).

Measurement of infiltration: After wheat crop was harvested in 2022-23, infiltration readings were taken. The measurements were made using a double-ring infiltrometer, which consisted of two concentric stainless-steel rings of radius 15 cm and 10 cm for outerand inner rings, respectively. The rings were implanted 5 cm deep into soilwith aid of a pouring plate and mallet, ensuring that small surface obstacles were removed to allow smooth insertion. A spirit level was used to certify both rings were at equal depth, while concentricity was checked with a steel tape. Flow rate of water through the inner ring was recorded under consistent environmental conditions. The infiltration rate (IR) was calculated by dividing the water depth *i.e.,* cumulative infiltration (I) that had infiltrated the soil during the corresponding time interval (t) using the following equation (Eq. 1):

$$IR(t) = \frac{d(I)}{d(t)}$$

Description of infiltration models: In the present study, three infiltration models were assessed: one empirical model (Kostiakov model) and two physically based models (Green & Ampt Model and Philip model). The experimentally observed infiltration data were fitted to these models, and the parameters for each model were determined by employing the linear and nonlinear regression analysis.

Empirical models

Kostiakov model: Kostiakov (1932) introduced one of the earliest models to estimate cumulative infiltration (CI), and the model is represented by the Eq. 2:

$$I = a\times t^{-(b+1)}$$

Here, "I"represents CI (cm), "t"denotes time (hr), and "a" and "b" are constants with a > 0 and 1 > b >0. These parameters, often referred to as Kostiakov's time exponent, are affected by soil texture and initial moisture conditions. To derive the IR, represented by "i", Eq. 2 was differentiated, yielding Eq. 3:

$$i = a \times t^{-b}$$

The parameters of the Kostiakov model were obtained by plotting the observed IR (i) against time (t). A power-law relationship was followed for curve fitting, where the coefficient in the equation was identified as "a", and the exponent was determined to be "b".

Physical process-based models

Green & Ampt Model: The Green & Ampt Model, introduced in 1911, provides a method for estimating the IR (I), expressed by the following equation (Eq. 4):

$$i = i_c + B \times I^{-1}$$

Here, "i"expressed in cm hr^{-1}, "i_c" is the steady state infiltration rate SSIR (cm hr^{-1}), "I" is the CI (cm), and "B" is a constant. A curve was generated by plotting "i" against "I^{-1}", and a linear relationship was used to fit this curve. The intercept of the curve corresponds to "i_c", while the slope represents the constant "B".

Philip model: In 1957, Philip familiarized an infinite series solution to Richard's equation to found a connection between cumulative infiltration (CI) and soil properties. The relationship is expressed in Eq. 5:

$$I = S \times t^{1/2} + K \times t$$

The derivation of this equation leads to an expression for the infiltration rate, given by Eq. 6:

$$i = \frac{1}{2} S \times t^{-1/2} + K$$

In these equations, "I" represents CI (cm), "i" is the IR (cm hr–1), "t" is time (hr), "S" is the sorptivity of soil (cm hr (-1/2), and "K" is the saturated hydraulic conductivity (HC) (cm hr^{-1}). The IR (i) was plotted against the reciprocal square root of time (t -1/2) to determine these parameters. The slope of the resulting best-fit curve corresponds to the value of "K", while the intercept provides the value of S/2.

Evaluation of model performance: The model performance was assessed by computing the "coefficient of determination" (R2), "root mean square error" (RMSE) (Eq. 7), "mean absolute error" (MAE) (Eq. 8) and "average relative error" (ARE) (Eq. 9). The R2 values indicate the percentage of total variance that the model accounts for, and it ranges from 0 (i.e.,no correlation) to 1 (i.e., perfect correlation). The MAE reflects the mean size of prediction errors, without considering their direction. The RMSE represents the square root of the average squared differences between predicted and observed values. The ARE was calculated to assess the model's fit, representing the mean ratio of the absolute error to the observed data.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\hat{Y}i-Yi)^2}$$

$$MAE = \frac{\sum_{i=1}^{n} |\hat{Y}i-Yi|}{n}$$

$$ARE = \left[\frac{1}{N}\sum_{i=1}^{n} \left(\frac{\hat{Y}i-Yi}{Yi}\right) \times 100\right.$$

Where, $\hat{Y}i$- represents predicted value and Yi is observed value.

Statistical Analyses: Different infiltration characteristics mentioned in the study were analyzed using ANOVA for a RCBD with three replications (Gomez and Gomez, 1984). Tukey's Honestly Significant Difference (HSD) test was performed as a post hoc mean separation test ($p < 0.05$) employing "agricolae" (Mendiburu, and Simon, 2007) package in R studio (Version 4.2.1).

Results and Discussion

Effects of CA–based practices on infiltration characteristics: The study found that different conservation agriculture and conventional tillage practices affected the infiltration rates, cumulative infiltration and steady state infiltration rate (Table 1). The IR varied across treatments, with the highest observed underthe PBB+R (21.02 cm hr^{-1}) and the lowest under the CT (9.94 cm hr^{-1}) (Table 1). The plots under ZT+R and PNB+R showed 80.7 and 93.8% higher IIR rate than CT and was at par with PBB+R. Plots without residue treatments, like PBB and PNB and ZT showed higher IR than CT by 61.7, 46.1 and 38.4%, respectively. The plots with residue retention have significantly improved IR (~43.0%) than plots without residue. The CA–based management practices showed 46.1–111.5% higher IR than the CT. Higher IRs under CApractices are likely due to the abundance

Table 1: Effect of CA– based practices on soil infiltration characteristics

Treatment	Initial infiltration rate (cm hr^{-1})	Steady state infiltration rate (cm hr^{-1})	Cumulative infiltration (cm)	Time to reach steady state (hr)
ZT+R	17.96^{a}	5.35^{a}	18.58^{b}	2.62^{a}
ZT	13.76^{b}	4.52^{b}	17.07^{b}	2.17^{b}
PBB+R	21.02^{a}	6.37^{a}	27.07^{a}	2.67^{a}
PBB	16.07^{b}	4.90^{b}	19.04^{b}	2.17^{b}
PNB+R	19.26^{a}	5.93^{a}	21.77^{ab}	2.58^{a}
PNB	14.52^{b}	4.52^{b}	17.81^{b}	2.33^{b}
CT	9.94^{c}	3.44^{c}	11.62^{c}	1.83^{c}

Table 2: Coefficients and parameters of infiltration models derived from least square fitting of experimental data under different CA–based practices

Treatment	Kostiakov model		Green &Ampt model		Philip model	
	a (cm ha^{-1})	b	i_c(cm ha^{-1})	B (cm^2 ha^{-1})	S (cm hr$^{-0.5}$)	K (cm ha^{-1})
ZT+R	7.13	0.36	4.72	21.15	70.30	2.44
ZT	6.52	0.32	5.61	10.14	47.06	3.65
PBB+R	10.26	0.34	8.67	25.80	79.20	5.30
PBB	7.20	0.37	6.20	15.08	61.06	3.55
PNB+R	8.00	0.33	5.58	23.50	70.78	3.27
PNB	6.78	0.36	6.34	11.65	53.52	3.81
CT	4.30	0.35	3.41	5.81	37.34	1.92

of macro-pores resulting fromthe roots of crop and activity of burrowing organisms (Atta-Darkwa *et al.,* 2022). The CT, on other hand, deteriorates soil structure by exposing the soil organic carbon (SOC) to microbial oxidation, which affects soil aggregation, resulting in surface sealing, closed pores, decreased infiltration rates, increased runoff and erosion (Bhattacharya *et al.,* 2020). Residue retention plots consistently demonstrated a significantly higher SSIR (35.4%) compared to plots where residue was removed. The PBB+R had the highest SSIR (6.37 cm hr^{-1}), depicting 85.2% increase over CT (3.44 cm hr^{-1}). Similarly, SSIRs in ZT+R and PNB+R were 55.5 and 72.4% higher, than the CT but at par with PBB+R. The improved SSIR under CA practices can be ascribed to higher SOC and enhanced soil aggregate stability (Amami *et al.,* 2021). This favorable soil structural condition resulted in improved porosity leading to enhanced infiltration rates (Aggarwal *et al.,* 2017). The PBB+R took significantly longer time to reach steady-state infiltration compared to CT, which may be attributed to superior soil structure, improved porosity and pore size distribution, and overall better soil health resulted from no tillage and residueretention (Amami *et al.,* 2021). Additionally, CA practices resulted in a 46.9 to133.0% increase in CI compared to CT, aligning with previous studies that reported higher soil CIin wheat crop under CA in -based systems (Rai *et al.,* 2018). In present study, PBB+R recorded the highest CI (27.07 cm), followed by PNB+R (21.77 cm), PBB (19.04 cm), ZT+R (18.58 cm), PNB (17.81 cm), ZT (17.07 cm), and CT (11.62 cm). The superior CI in PBB+R was mainly due to higher SOM, improved soil aggregation, more profuse macropores, and an increased permeable soil structure (Adak *et al.,* 2019; Raj *et al.,* 2023).

Effects of CA–basedpractices on estimated parameters of infiltration models: The estimated parametersof infiltration models—Kostiakov, Green & Ampt, and Philip—are shown in Table 2. It was observed that the model parameters differed among treatments. The "a" parameter of Kostiakov model reflects the initial infiltration rate. The highest estimated "a" value was noticed in the PBB+R (10.26 cm hr^{-1}) system, while the lowest was in the CT (4.30 cm hr^{-1}) production system. Compared to CT, "a" value in ZT+R, PBB+R, and PNB+R were higher by 65.8, 138.6, and 86.0%, respectively (Table 2; Fig. 1). These findings suggest that the PBB+R system facilitates greater water infiltration into soilthan CT production system.

The Kostiakov model exponent coefficient "b" ranged from 0.32 to 0.37, consistent with the value (b <1) reported by Atta-Darkwa *et al.,* (2022). In Green & Ampt model, "ic" parameter represents SSIR, which was highest in PBB+R (8.67 cm hr^{-1}) and lowest in CT (3.41 cm hr^{-1}) (Table 2 and Fig. 2), aligning with experimental observations. However, the model tended to overestimate the SSIR across all treatments. The parameter "B" in the Green & Ampt model, which is influenced by the initial infiltration rate, was lowest in the CT (5.81 cm^2 hr^{-1}), matching field experiment observations (Fig. 2; Table 2). However, the model underestimated the initial infiltration rate for plots without residue

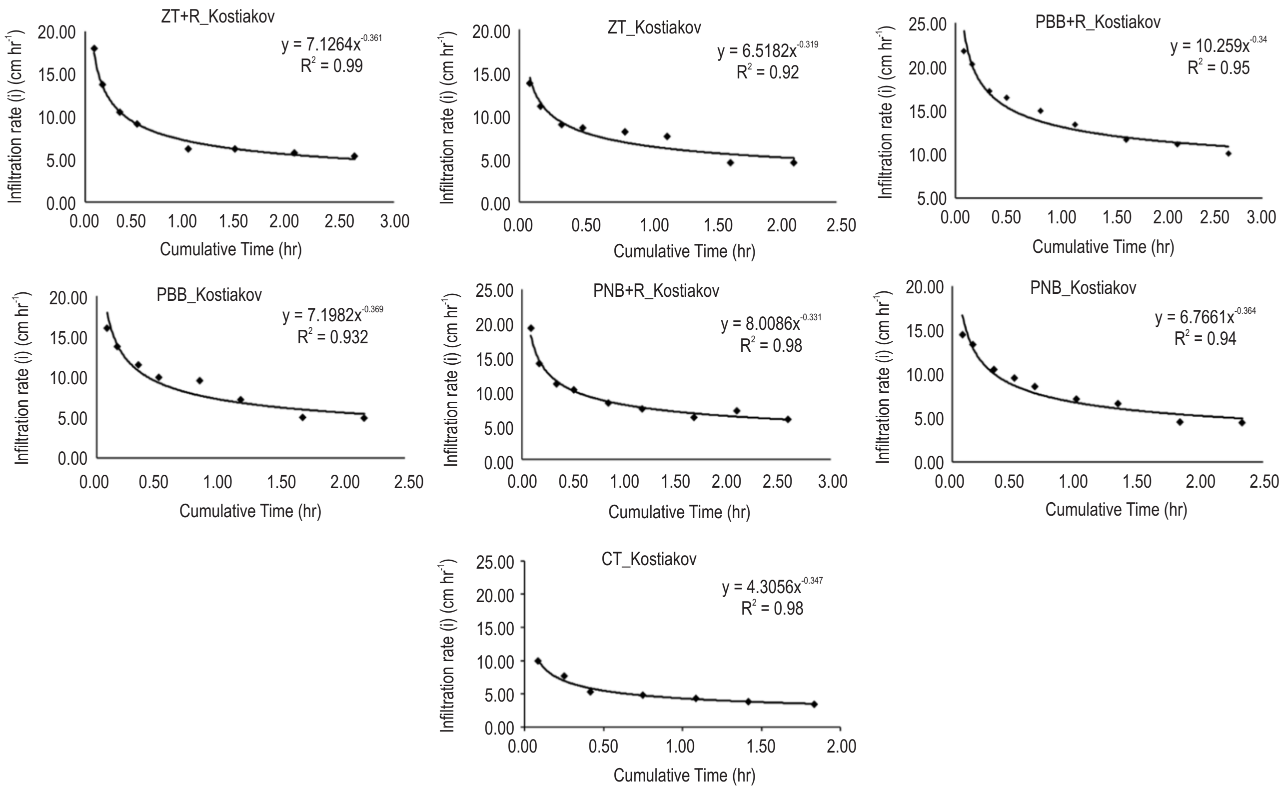

Fig. 1: Kostiakov model [Infiltration rate (i) vs Cumulative time (t)] under different CA–based practices.

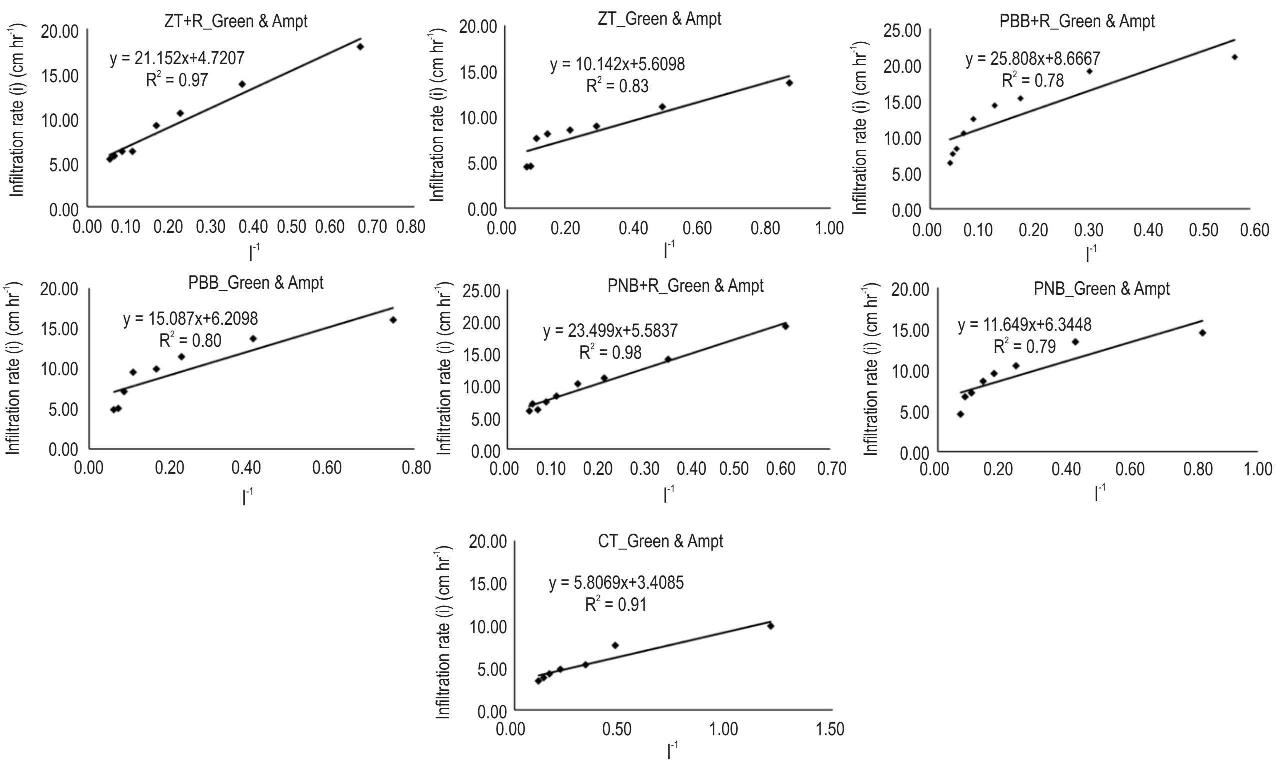

Fig. 2: Green and Ampt model [Infiltration rate (i) vs 1/ Cumulative Infiltration(I^{-1})] under different CA–based practices.

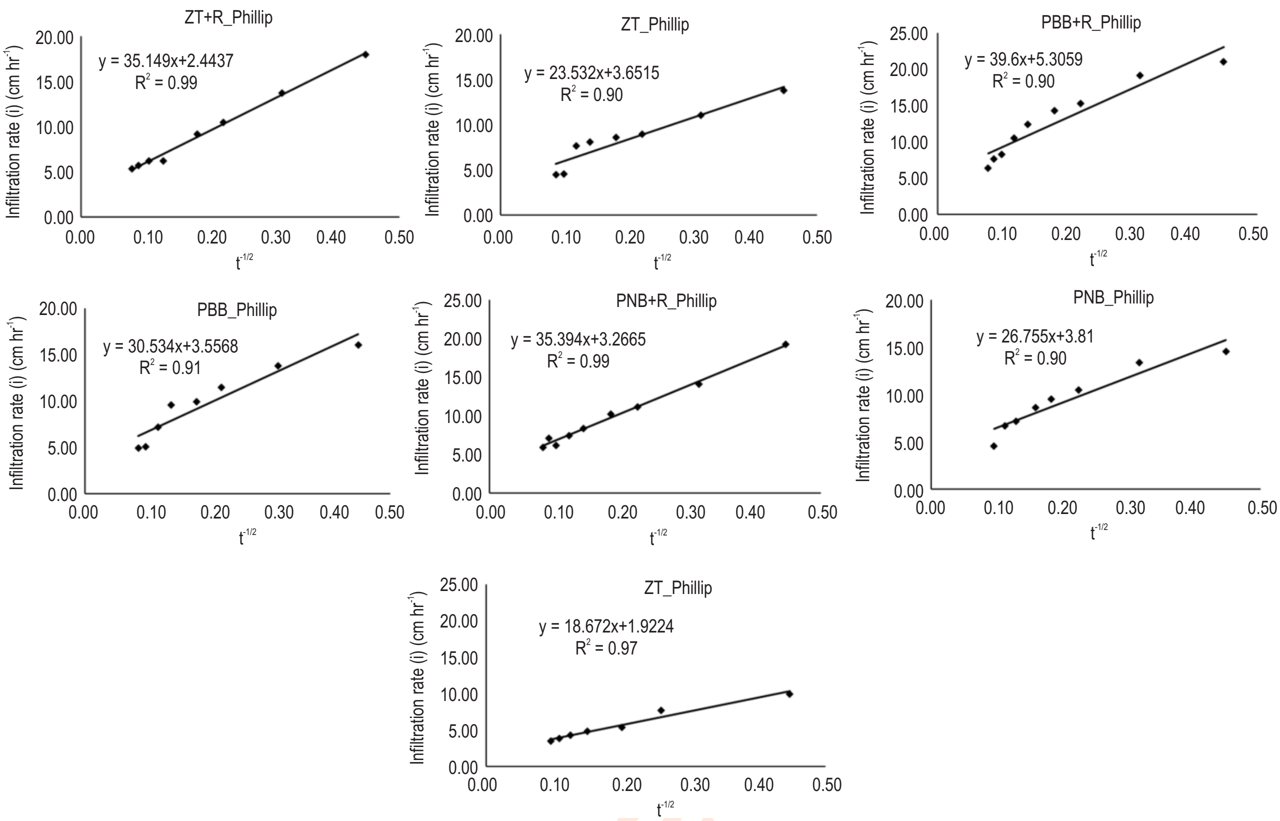

Fig. 3: Philip model [infiltration rate (i) vs $t^{-1/2}$] under different CA–based practices.

Table 3: Assessment of infiltration models under different CA–based practices

Treatments	R^2	RMSE	MAE	ARE
Kostiakov model				
ZT+R	0.99	0.39	0.27	0.17
ZT	0.92	0.84	0.75	0.76
PBB+R	0.95	1.26	0.96	0.41
PBB	0.92	1.08	0.89	0.69
PNB+R	0.98	0.53	0.43	0.18
PNB	0.94	0.93	0.76	0.49
CT	0.98	0.33	0.23	0.15
Green and Ampt model				
ZT+R	0.97	0.77	0.72	1.57
ZT	0.83	1.17	1.08	4.20
PBB+R	0.78	2.24	2.09	2.79
PBB	0.80	1.66	1.56	5.82
PNB+R	0.98	0.65	0.53	1.05
PNB	0.79	1.71	1.41	10.14
CT	0.91	0.65	0.45	1.95
Philip model				
ZT+R	0.99	0.31	0.24	0.27
ZT	0.90	0.92	0.76	2.83
PBB+R	0.91	1.46	1.37	2.83
PBB	0.90	1.15	1.83	3.40
PNB+R	0.99	0.38	0.30	0.29
PNB	0.91	1.05	0.89	6.76
CT	0.97	0.40	0.29	0.77

(PBB, ZT, PNB, and CT) and overestimated it for plots with retained residue (PBB+R, ZT+R, and PNB+R). The highest soil sorptivity (S) value according to the Philip model was found in PBB+R>followed by PNB+R>, ZT+R> PBB> PNB>ZT> CT, respectively (Fig. 3; Table 2). The variations in "S" values according to Philip's model is caused by the existence of unperturbed, interconnected pores maintainedby residue mulch and improvedsoil microbial growth, which lead to a faster infiltration rate in CA-based managements (Hangen *et al.,* 2002). The "S" values under CA practices were 26.0 to 112.1% higher than that of CT. This increase in "S" is likely due to the higher moisture content under CA–based practices, which decrease evaporation and increase infiltration rates (Atta-Darkwa *et al.,* 2022). The "K" value of the Philip model, which represents saturated HC is given in Table 2.

Assessment of infiltration model'sperformance for estimating infiltration rate: The perusal of data in Table 3 showed indicated that R^2 ranged from 0.78 to 0.99, RMSE 0.31 to 2.24 cm hr^{-1}, MAE 0.23 to 2.09 cm hr^{-1}, and ARE 0.15 to 10.14 cm hr^{-1}, across various models. Among the tested models, the Kostiakov model exhibited the best fit with the highest R^2 (0.92 to 0.99) and the lowest error metrics (RMSE of 0.33–1.26 cm hr^{-1}; MAE of 0.23–0.96 cm hr^{-1}; ARE of 0.15–0.76 cm hr^{-1}). The Philip model also performed well, with $R^2 \geq 0.90$, RMSE ≤ 1.46 cm hr^{-1}, MAE ≤ 1.83 cm hr^{-1}, and ARE ≤ 6.76 cm hr^{-1}. The Green & Ampt model showed good accuracy with $R^2 \geq 0.78$, RMSE ≤ 2.24 cm hr^{-1}, MAE ≤ 2.09 cm hr^{-1}, and ARE ≤ 10.14 cm hr^{-1}. The findings suggested that the empirical Kostiakov model aligns more closely with the experimental data compared to the physical models, i.e., Green &Ampt and Philip model, owing to the fact that the empirical model rely more on experimental data without oversimplified assumptions (Amami et al., 2021). In contrast, the Green & Ampt and Philip models, which are grounded in physical principles, but struggled when basic statistical curve-fitting techniques were applied to determine their coefficients (Rai et al., 2018; Ghosh et al., 2020).

Among the treatments, PBB+R demonstrated the highest initial and steady-state infiltration rates, along with the greatest cumulative infiltration. Additionally, PBB+R took the longest time to achieve the steady-state infiltration rate, indicating that an extended use of conservation agriculture techniques can enhance the soil structure and facilitate efficient soil water distribution throughout the profile. The assessment of the model performance revealed that the simple empirical Kostiakov infiltration models more accurately depicted the relationship between infiltration rate and time, offering the best fit for field data collected during study. Consequently, Kostiakov model is highly effective and can be applied to optimize tillage and irrigation management at the experimental site or in other areas having similar soil characteristics. Future research can be conducted to explore the relationship between soil structural variables and infiltration characteristics using statistical methods or physically–based models.

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Data availability: All the data analyzed for this study are included. Any extra data of interest if needed are available from the Corresponding author upon reasonable request.

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