Estimating ET_O and scheduling crop irrigation using Blaney–Criddle equation when only air-temperature data are available and solving the issue of missing meteorological data in Egypt

R.E. Abdelraouf[1,*], *M.A.* El-Shawadfy[1], *A.B.* Bakry[2], *H.K.* Abdelaal[1], *M.A.* El-Shirbeny[3], *R.* Ragab[4], and *S.L.* Belopukhov[5]

[1]Water Relations and Field Irrigation Dept., National Research Centre, Dokki, Giza, Egypt
[2]Field Crops Dept., National Research Centre, Dokki, Giza, Egypt
[3]National Authority for Remote Sensing and Space Sciences (NARSS), Cairo, Egypt,
[4]UK Center for Ecology and Hydrology (UKCEH), Wallingford, United Kingdom
[5]Russian State Agrarian University-Moscow Timiryazev Agricultural Academy, 127434, 49, Timiryazevskaya Street, Moscow, Russian Federation

Abstract. Accurate assessment of evapotranspiration is essential for crop irrigation planning. In developing countries and given the cost of evaluating evapotranspiration based on the Penman-Monteith equation, this research is an attempt to provide a simple equation that depends only on temperature to estimate evapotranspiration and serve as an alternative method to FAO56-PM when only air temperature data are available and the problem of missing meteorological data is solved. Four reference methods for evapotranspiration (ET) were compared under the local climatic conditions of the El-Nobaria region in northern Egypt. The Blaney–Criddle method was found to have the highest correlation with the FAO56-PM method. Using the simple equations to calculate ETo for irrigation scheduling of peanuts had a positive effect on the yield and yield components of peanuts. The highest productivity value was obtained when the Blaney–Criddle equation was used to estimate peanut irrigation scheduling, while equation resulted in lower productivity. When the equation was used, the differences in productivity between the equations were highly significant. It is worth noting that when the Blaney–Criddle and Thorthwaite equations were used, followed by the FAO56-PM equation, the superiority of the water productivity value became evident, as the increase in nutrient concentration in the root zone led to increased nutrient uptake, resulting in an increase in the productivity of peanut yield, oil and protein.

1 Introduction

The gap between food production and the food needs of the population can be reduced through improved agricultural practices such as irrigation, especially in arid areas [5, 6, 7].

[*] Corresponding author: h.kamal2007@gmail.com

In Egypt, crop water productivity (WP) is of great importance, especially since water resources for irrigation are limited [8]. Water stress is the main reason for lower crop yields worldwide. Hence, the use of irrigation water should be appropriate and the principles of deficit irrigation with low yield reduction must be accepted [9]. Evapotranspiration (ET) is the loss of water to the atmosphere through the combined processes of evaporation from the soil and plant surface and transpiration from plants [10]. The estimation of evapotranspiration is one of the most important hydrological components for determining the water balance and becomes essential for calculating a reliable recharge and evapotranspiration rate for groundwater flow analysis. Hence, a reliable and consistent estimation of evapotranspiration is of great importance for the efficient management of water resources. Since direct measurement of ETo for short grass is difficult, time-consuming, and costly, the most practical approach would be to estimate ETo based on climatic variables such as solar radiation, air temperature, wind speed, and relative humidity. Various methods are available for estimating ETo, with equations ranging from the most complex energy balance method, which requires detailed climatological data [10], to simpler methods with less data [11]. Among them is the modified Penman-Monteith (PM) method [10]. However, the main disadvantage of the modified PM method is that it requires air temperature, relative humidity, wind speed, and solar radiation, which are not readily available in some locations [12]. On the other hand, simpler equations such as the Thornthwaite method [2] are popular methods in places with scarce meteorological data, as they only require the monthly average air temperature. [13] pointed out that the Thornthwaite method was developed for temperatures measured under potential conditions and that it only reflects potential evaporation when there is no stress with soil moisture. Therefore, this method tends to overestimate the potential evaporation in dry regions. The equation uses only solar radiation (Rs), net radiation (Rn), and mean daily temperature (Tm) as input parameters to estimate ETo. To date, there are more than 57 equations for calculating reference evapotranspiration. After reviewing all previous equations for estimating reference evapotranspiration, it was found that most equations depend on many climate factors in their estimation, except for four equations that depend only on air temperature, and these are [1, 2, 3, 4]. The aim of this study is to provide a simple equation as an alternative to the FAO56-PM when only air temperature data are available and to solve the problem of missing meteorological data. It is used to plan irrigation of crops under drought conditions in Egypt (Peanut Irrigation Case Study).

2 Materials and Methods

2.1 Location and climate of experimental site

The field experiments were conducted during the 2022 and 2023 growing seasons at the research farm station of the National Research Centre (NRC) (latitude 30° 30' 1.4"N, longitude 30°19' 10.9" E, and 21 m + MSL (mean sea level)) in Al-Nubaria, Al-Buhayrah Governorate, Egypt. The experimental area has an arid climate with cool winters and hot dry summers. The data of average temperature, relative humidity and wind speed were taken from the the meteorological data of the Central Laboratory for Agricultural Climate (CLAC), Agricultural Research Centre for El-Nubaria region, as shown in Figure (1).

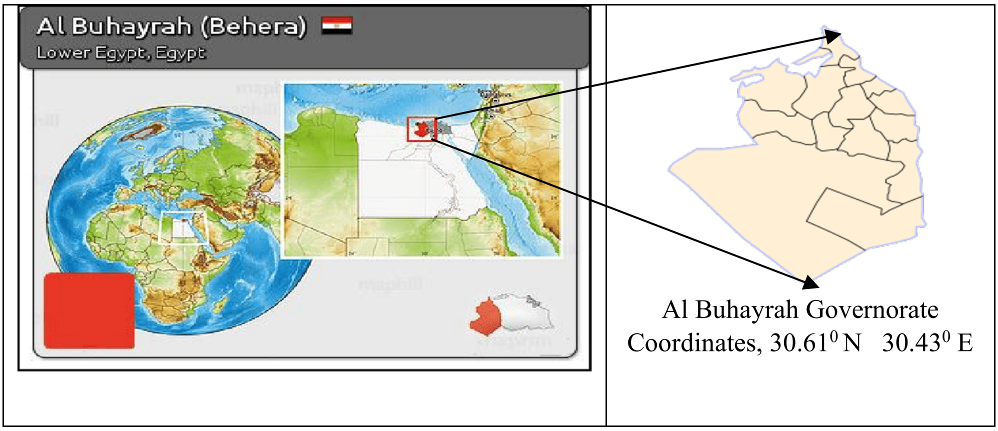


Fig. 1. Study area and some climate data for El-Nubaria region, Egypt.

2.2 Physical and chemical properties of the soil and irrigation water

The source of irrigation water was an irrigation canal that ran through the experimental area. The irrigation water had a pH of 7.38 and an electrical conductivity (EC) of 0.44 dS m-1. The most important physical and chemical properties of the soil are listed in Table (1).

Table 1. Physical and chemical properties of the soil of the experimental area

Soil layer depth (cm)	0–15	15-30	30-45
Texture	Sandy	Sandy	Sandy
Bulk density (t m^{-3})	1.67	1.64	1.66
$EC_{1:5}$ (dS m^{-1})	0.45	0.52	0.66
pH (1:2.5)	8.53	8.51	8.84
Total $CaCO_3$ (%)	7.15	2.46	4.67

2.3 Experimental design

The experimental design was a randomized complete block design with three replicates. An irrigation schedule for the peanut crop was established based on the four equations for estimating evapotranspiration from air temperature and compared with the irrigation schedule, resulting from the modified Penman-Monteith equation. For accurate crop irrigation scheduling, the monthly average reference evapotranspiration values for the studied equations in mm/month were converted to daily average values in mm/day.

2.4 Equations

2.4.1 The (FAO56) Penman-Monteith equation

The FAO Penman–Monteith method for calculating ETo can be expressed as [10]:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad \ldots\ldots\ldots \quad \ldots..(1)$$

ETo is the evapotranspiration of the reference plant (mm day-1), Δ is the slope of the saturation vapor pressure vs. air temperature curve (kPa °C-1), Rn is the net radiation at the plant surface (MJm-2 day-1), G is the soil heat density at the soil surface (MJm-2 day-1), γ is the psychrometric constant (kPa °C-1), Ta is the average daily air temperature at 1.5–2.5 m height (°C), u2 is the average daily wind speed at 2 m height (m s-1), es is the saturation vapor pressure (kPa) and ea is the actual vapor pressure (kPa).

2.4.2 Blaney–Criddle equation

The Blaney–Criddle equation one from best equations when only air-temperature datasets are available for a site.

$$\mathrm{ET}_0 = P(0.457\mathrm{T}_{mean} + 8.128) \ldots \qquad \ldots\ldots\ldots..(2)$$

Where: ETo is the reference evapotranspiration [mm day^{-1}] (monthly)
T mean is the mean daily temperature [°C] which is given as T mean = (T max + T min)/ 2
P is the mean daily percentage of annual daylight hours.

2.4.3 Thornthwaite equation

The Thornthwaite equation given by [2] is

$$\mathrm{ET}_0 = 16 \times \left(\frac{10T_i}{I}\right)^a \left(\frac{N}{12}\right)\left(\frac{1}{30}\right) \ldots\ldots\ldots \qquad \ldots..(3)$$

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514} \quad \text{and} \quad a = (492390+17920I-771I^2+0.675I^3) \times 10^{-6}$$

Where Ti is the average monthly temperature [°C], N is the average monthly sunshine duration in hours. The main advantage of this method is that only the temperature information is required in addition to the hours of sunshine. In general, it is known that the Thornthwaite method leads to an underestimation in dry areas, while it leads to an overestimation in humid areas.

2.4.4 Kharrufa (1985)

$$\mathrm{ET_o} = 0.34 \times p \times \mathrm{T_a}^{1.30} \ldots \qquad \ldots\ldots\ldots..(4)$$

ETo is the evapotranspiration of the reference plants (mm day-1), p is the mean annual percentage of daylight hours for different latitudes and Ta is the average daily air temperature (°C).

2.4.5 Linacre (1977)

$$ET_o = \frac{\frac{700(T_a+0.006\,h)}{(100-A)} + 15(T_a - T_{dew})}{80-T_a} \ldots\ldots \quad \ldots \qquad \ldots..(5)$$

ETo is the evapotranspiration of the reference plant (mm day-1), Ta is the average daily air temperature (°C), h is the altitude (m), A is the latitude (degrees) and Tdew is the dew point temperature (°C).

Irrigation requirement of peanut crop for each equation: ETo was estimated for each equation and the results are shown in Fig. (2). Daily irrigation water was calculated by equation (6) and seasonal irrigation water under a drip irrigation system is summarized in Table (2):

$$IRg = \left[\frac{ETO \times Kc \times Kr}{Ei}\right] - R + LR \ldots \qquad \ldots\ldots(6)$$

Where: IRg = gross irrigation requirement, mm day-1; ETO= reference evapotranspiration, mm day-1 , Kc = crop factor (FAO-56); Kr = land cover reduction factor and the values of Kr measured by the Keller equation: Kr = GC% + 0, 15. (1 – GC %), where GC%: Ground cover = (shaded area per plant/area per plant); Ei = Irrigation efficiency, %, R = Water received by the crop from sources other than irrigation, mm (e.g. rainfall), LR = Amount of water required for leaching of salts, mm. The total amounts of water for each treatment and the biochar application rate were given in Table (3).

Table 2. Different irrigation requirements of peanut plant based on each ETo equation.

Seasons	Different irrigation requirements of peanut plant based on each ETo equation, m^3 ha^{-1}				
	Penman-Monteith	Blaney–Criddle	Thornthwaite equation	Kharrufa (1985)	Linacre (1977)
2022	5309	4290	4250	7481	8804
2023	4957	3982	4098	7438	8671
% relative to FAO-56 PM		80.81	80.05	140.91	165.83
		80.33	82.67	150.05	174.92

2.5 Climatic parameters required by each equation

One of the most important considerations when introducing a simple method that deviates from the standard method such as the Penman-Monteith equation (FAO56-PM) is the high probability of unavailability and unreliability in the measurement and collection of weather data. In general, setting up the equipment for meteorological measurement in remote areas and in a specific location is difficult. Table (3) shows the data requirements for the FAO56-PM, Blaney–Criddle, Thornthwaite, Kharrufa and Linacre equations respectively.

Table 3. Comparison of each in terms of the number of parameters required.

Variables	ETo equations				
	Penman-Monteith equation	Blaney–Criddle equation	Thornthwaite equation	Kharrufa (1985) equation	Linacre (1977) equation
Temperature	Essential	Essential	Essential	Essential	Essential
Humidity	Essential	-------	-------	-------	-------
Wind speed	Essential	-------	-------	-------	-------
Radiation	Essential	-------	-------	-------	-------
No. of daylight hours	-------	Essential	Essential	Essential	Essential
Saturated vapor pressure	Essential	-------	-------	-------	-------

2.6 Parameters Evaluation

2.6.1 Correlation of ETo of different methods relative to FAO56-PM

A correlation was established between the four simple equations and the modified Penman-Monteith equation, (2) Nitrogen concentration in the soil in the root zone: The average nitrogen concentration in the collected soil samples in the root zone was measured two hours after irrigation during the two growing seasons (2017 and 2018), (3) Yield and yield components: At harvest, a random sample of 10 plants was taken from each plot to determine the number and weight of pods/plant, number and weight of seeds/plant.

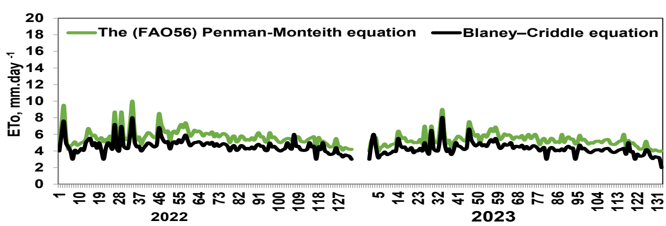
$$\text{WP peanut} = \frac{\text{Ey}}{\text{Ir}} \ldots\ldots\ldots \qquad \ldots(7)$$

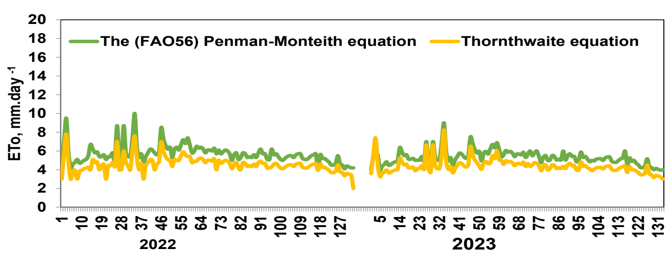
Where: WP peanut is the water productivity of peanut (kg peanut m-3 water), Ey is the economic yield (kg ha-1); Ir is the amount of irrigation water applied (m3 water /ha/season), (5) Oil content and oil yield: the oil content in seed was determined according to the method described by [14] and the oil yield/ha was calculated by multiplying the seed yield by the oil content of the seed. (6) Protein content and protein yield: The protein content of the seeds was calculated by multiplying the total nitrogen concentration by 6.25 according to the method described by [14]. Statistical analysis: all the data obtained from the two seasons of the study were statistically analyzed using the method of analysis of variance according to [15], calculating the values of least significant differences (L.S.D. at 5% level) to compare the mean values of the different treatments.

3 Results and discussions

3.1 Correlation of ETo of different methods relative to FAO56-PM

The high correlation of ETo by the Blaney–Criddle and Thorthwaite method with the FAO56-PM method clearly shows the importance of temperature. This fact is also confirmed by many studies showing that the ETo determined by the Blaney–Criddle method was close to the ETo of the Penman-Monteith equation (FAO56-PM). Therefore, it could be suggested to use the Blaney–Criddle method when meteorological data are not available. There are two equations whose values are slightly lower than those of the FAO-56 PM, but their correlation coefficient R2 is high. These are the Blaney–Criddle and Thorthwaite equations. In contrast, two other equations, [3, and 4] equations, show an overestimation of the FAO-56 PM values and their correlation coefficient R2 is lower than that of the other equations, as shown in the following figures (3) and (4).





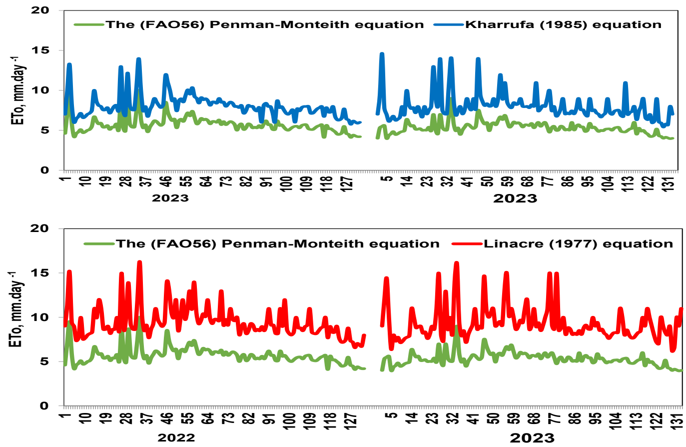


Fig. 3. ETo of the simple different methods compared to FAO56-PM

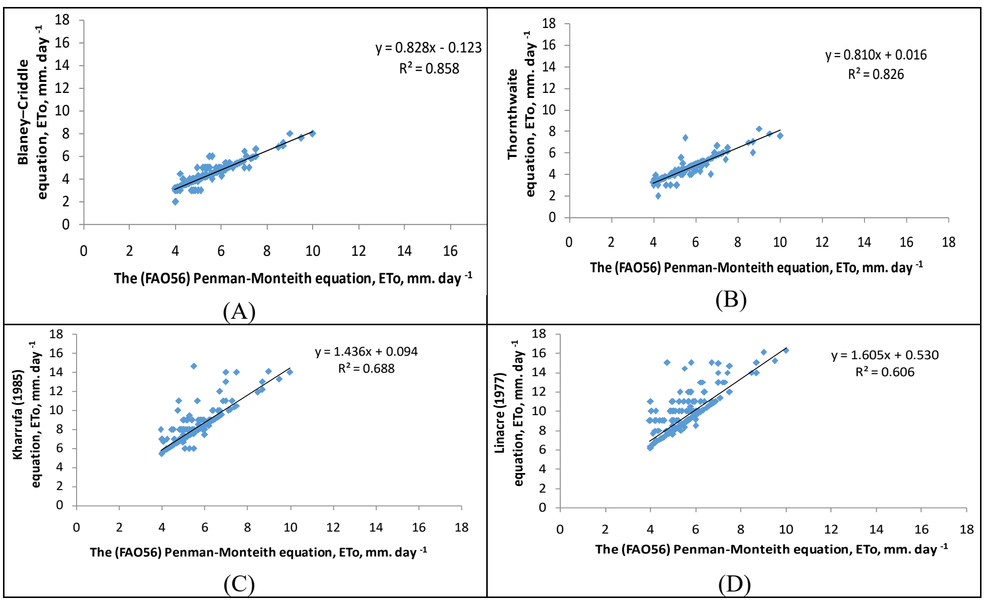


Fig. 4. Regression analysis for the ET_o estimates of (A) Blaney–Criddle (B) Thornthwaite (C) [3] and (D) [4] against FAO56-PM for evaluation years of 2022 and 2023 at El-Nobaria region, Egypt.

Figure (5) shows the relationship between the volumes of irrigation water added as calculated by the four ETo evaporation equations and the nitrogen concentration in the soil. It is clear from the figure that there is an inverse relationship between the volume of the added irrigation water and the concentration of nitrogen in the soil. From the figure, the higher the volume of irrigation water, the higher the dilution and the lower the nitrogen concentration in the root zone. Blaney-Criddle and Thornthwaite had a close concentration, with a very small, insignificant difference, while the soil nitrogen concentration was lower under plots irrigated, according to [3, and 4] estimation of ETo due to the relatively larger water volume added.

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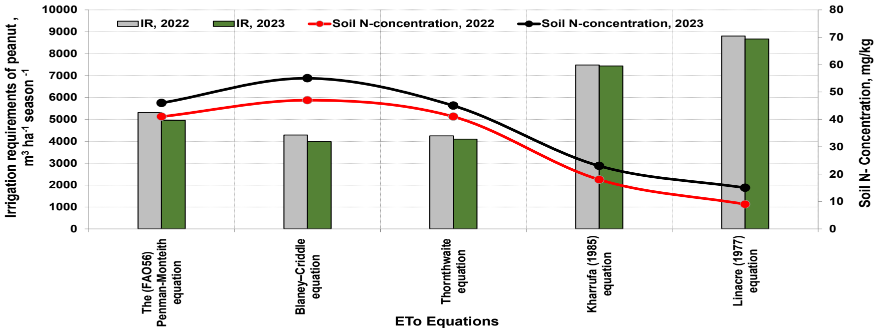

Fig. 5. Effect of volume of the added water on the soil nitrogen concentration in the root zone

3.2 Yield and yield components of peanut

Figure (6) and the data in Table (4) show the effect of irrigation scheduling, which was calculated based on simple equations of ETo, i.e., [1, 2, 3, and 4], compared to the FAO56-PM equation, on the yield and yield components (biological yield, pod yield, and seed yield) of the peanut crop in the 2022 and 2023 experimental seasons. In both seasons, data showed that the higher values for biological yield, pod yield, and seed yield of the peanut crop were found when using either Blaney-Criddle or Thorthwaite equations followed by the FAO56-PM equation. This may be due to the amount of applied water for irrigation being very similar under both equations. While the lowest values were obtained by [3, and 4] equations, The highest value of productivity was when using the Blaney-Criddle equation in estimating irrigation scheduling for peanut crops, while it was less productive when using [4] equation. The differences between them were highly significant. This is due to the increase in the concentration of nutrients, especially nitrogen, with lower rates of water addition and the difficulty of leaching these elements from the root zone, while these elements were leached with high rates of added irrigation water.

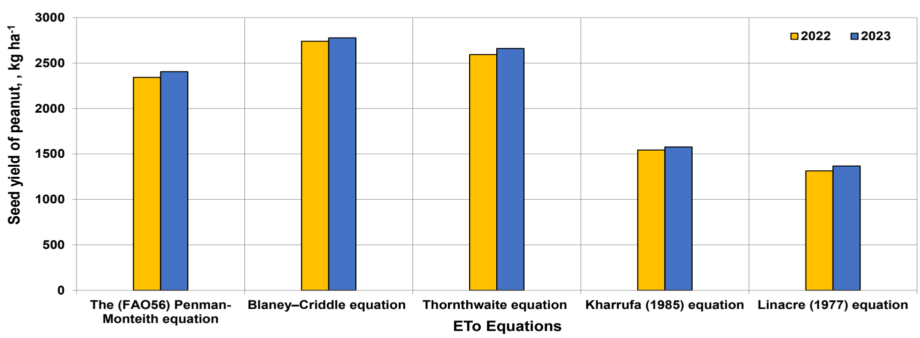

Fig. 6. Effect of irrigation scheduling based on simple equations other than the complex equation of Penman Monteith on the productivity of peanut

3.3 Water productivity of peanut

The water productivity (WP) parameter of the peanut crop in the two experimental seasons of 2022 and 2023 (Table 4) Data showed that water productivity in both seasons was significantly affected by irrigation scheduling, which was calculated based on simple equations of ETo calculation compared to the FAO56-PM equation. It is worthy to mention that when using both Blaney-Criddle and Thorthwaite equations, the FAO56-PM equation exhibited its superiority in water productivity.

Table 4. Effect of irrigation scheduling based on simple equations other than the equation of Penman Monteith on the yield and yield components of peanut

	ET_0 Equations	Biological Yield, ton ha^{-1}	Pod yield, ton ha^{-1}	Seed Yield, kg ha^{-1}	WP, kg m^{-3}
2022	FAO56-PM equation	6.687 c	3.897 b	2343 b	0.440
	Blaney–Criddle	7.773 b	4.367 b	2740 a	0.647
	Thornthwaite	6.880 a	4.643 a	2593 a	0.607
	Kharrufa1985	5.227 d	3.210 c	1543 c	0.207
	Linacre 1977	3.560 e	2.230 d	1314 d	0.153
	LSD	0.838	0.542	199.9	
2023	FAO56-PM equation	7.030 c	4.093 b	2405 b	0.487
	Blaney–Criddle	7.287 b	4.630 b	2778 a	0.673
	Thornthwaite	7.347 a	4.950 a	2661 a	0.673
	Kharrufa1985	5.557 d	3.447 c	1577 c	0.213
	Linacre 1977	3.817 e	2.410 d	1368 d	0.160
	LSD	0.8250	0.5489	206.1	

WP_{peanut}: Water Productivity of peanut

3.4 Oil and protein yields

Significant differences were detected regarding the oil percentage as well as the oil yield of the peanut crop in the 2022 and 2023 growth seasons (Table 5). It could be concluded that when using both Blaney-Criddle and Thorthwaite equations followed by the FAO56-PM equation, a significant increase in oil (%) and oil yield was obtained compared with the other equations [3, and 4]. Results tabulated in Table 5 also indicate that the highest values of protein percentage and protein yield were observed by using Blaney-Criddle or Thorthwaite equations followed by the FAO56-PM equation in the first and second seasons. On the other hand, using both [3, and 4] equations showed the lowest values. This may be due to the increase in the concentration of nutrients in the root zone, which results in increased absorption and an increase in the productivity of peanuts from oil and protein.

Table 5. Effect of irrigation scheduling based on simple equations other than equation of FAO-56 PM on oil content and oil yield and protein content and protein yield of peanut seeds

Growing seasons	ET_o Equations	Oil, %	Oil yield, kg/ha	Protein, %	Protein yield, kg/ha
2022	FAO56-PM equation	45.0	1054.4	23.0	538.7
	Blaney–Criddle	47.0	1287.8	26.0	713.0
	Thornthwaite	46.7	1210.9	24.0	622.3
	Kharrufa1985	41.0	632.6	15.0	231.7
	Linacre 1977	43.0	565.0	12.3	163.0
	LSD	3.2	107.9	2.4	74
2023	FAO56-PM equation	47.7	1147.2	24.0	577.3
	Blaney–Criddle	50.0	1389.0	27.3	759.3
	Thornthwaite	45.0	1197.5	25.3	674.3
	Kharrufa1985	43.0	678.1	16.3	257.7
	Linacre 1977	39.0	533.5	14.0	192.0
	LSD	3.1	95.1	2.2	61.4

4 Conclusions

The study concludes with the possibility of using the Blaney-Criddle equation or the Thornthwaite equation in estimating evapotranspiration, which only needs air temperature as an effective alternative to the FAO56-PM equation, which needs more meteorological data and weather stations**.** An approach to evapotranspiration calculation that is comparatively simple is the Blaney-Criddle equation. Generally, the Penman-Monteith equation is preferred when there is an adequate amount of meteorological data available. Nonetheless, the Blaney-Criddle formula works best when a site's air temperature datasets are the only ones available.

References

1. H.F. Blaney and W.D. Criddle, Determining water requirements in irrigated area from climatological and irrigation data. Soil conservation service technical paper 96, Soil conservation service (US Department of Agriculture, Washington, DC, 1950).
2. C.W. Thornthwaite, Geographical Review, **38(1),** 55-94 (1948). https://refhub.elsevier.com/S2095-6339(15)30090-3/sbref57.
3. N.S. Kharrufa, Beitr.Zur. Hydrol., **5**, 39-47 (1985). https://refhub.elsevier.com/S0378-3774(21)00655-7/sbref35.
4. E.T. Linacre, Agric. Meteorol., **18(6),** 409-424 (1977). https://doi.org/10.1016/0002-1571(77)90007-3.
5. R.E. Abdelraouf, S.F. El-Habbasha, M. Hozayn, E. Hoballah, Journal of Applied Sciences Research, **9 (3),** 2135-2145 (2013).
6. R.E. Abdelraouf, M.A. El-Shawadfy, A. Fadl, Plant Archives, 20 (1), 3505-3518.
7. M. A. Marwa, R.E. Abdelraouf, S. W. Wahba, K. F. El-Bagouri, and A.G. El-Gindy, Agricultural Engineering International: CIGR Journal, Special issue, 174–183 (2017).
8. M. Hozayn, A.A. Abd El Monem, R.E. Abdelraouf, M.M. Abdalla, Journal of Agronomy **(34)**, 1- 10 (2013).
9. I. M. El-Metwally, R. E. Abdelraouf, M. A. Ahmed, O. Mounzer, Juan José Alarcón and M. T. Abdelhamid, Agriculture (Poľnohospodárstvo), **61 (1),** 22−32 (2015).
10. G. R. Allen, L. S. Pereira, D. Raes, and M. Smith, Crop Evapotranspiration-Guidelines for computing crop water requirements, (FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy, 1990) 878-86.
11. G.H. Hargreaves, and Z.A. Samani, Appl. Eng. Agric., **1(2),** 96-99(1985) https://doi.org/10.13031/2013.26773.
12. S. Irmak, J. O. Payero, D. L. Martin, A. Irmak, & T. A. Howell, Journal of Irrigation and Drainage Engineering, **132,** 564–578 (2006). https://doi.org/10.1061/ (ASCE)0733-9437(2006)132:6(564)
13. Y. Mintz, and G. K. Walker, J. Appl. Meteorol, **32,** 1305–1334 (1993) MGA Abstract
14. A.O.A.C. Association of Official Agricultural Chemists. Official Methods of Analysis. 4th ed. pp. 495-510. (Benjamin Franklin Station, Washington. D.C., U.S.A., 1990)
15. G. W. Snedecor, and W. G. Cochran, Statistical Methods. Oxford and J.B.H. publishing com. 7th edition, **593**, 1216 (1980)