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Review Article

Surface Renewal Application for Estimating Evapotranspiration: A Review

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The estimation of evapotranspiration (ET) is essential for meteorological modeling of surface exchange processes, as well as for the agricultural practice of irrigation management. Hitherto, a number of methods for estimation of ET at different temporal scales and climatic conditions are constantly under investigation and improvement. One of these methods is surface renewal (SR). Therefore, the premise of this review is to present recent developments and applications of SR for ET measurements. The SR method is based on estimating the turbulent exchange of sensible heat flux between plant canopy and atmosphere caused by the instantaneous replacement of air parcels in contact with the surface. Additional measurements of net radiation and soil heat flux facilitate extracting ET using the shortened energy balance equation. The challenge, however, is the calibration of SR results against direct sensible heat flux measurements. For the classical SR method, only air temperature measured at high frequency is required. In addition, a new model suggests that the SR method could be exempted from calibration by measuring additional micrometeorological variables. However, further improvement of the SR method is required to provide improved results in the future.

1. Introduction

Agrometeorology deals with the interaction between climate and agriculture and the processes of energy and mass exchange between biosphere and atmosphere. It also focuses on the climatic processes at time scales ranging from seconds to more than a decade. However, the most important agrometeorological variables influencing crop growth and development are air temperature, net radiation, and precipitation. Air temperature has a direct impact on vegetative and reproductive development; that is, high temperature can reduce the development rate and vice versa; likewise, solar radiation stimulates energy that affects the photosynthesis and biomass production of the individual plant constituents [1].

Evapotranspiration (ET) is a process by which water undergoes a phase change from liquid to vapour with little temperature change and the removal of the vapour from the surface to air. It includes transpiration that represents the major use of irrigation and rainfall water by plants in agricultural areas and evaporation from the soil [2]. ET occurs under the influence of a number of climatic and biological factors, representing 60% of total precipitation reaching land surfaces [3, 4]. Likewise, different micrometeorological methods have been used for the estimation of ET, such as Bowen Ratio (BR), Eddy Covariance (EC), Optical Scintillation (OS), and weighing lysimeter methods. These methods are expensive and the sensors used are sensitive and vulnerable to damage and require extensive fetch and site homogeneity [5].

The EC method is the most reliable among all other methods with respect to the estimation of ET, due to a direct estimation of water vapour exchange between the atmosphere and plant canopy [6]. EC systems are extensively used for ET estimation due to the ability to obtain direct and reliable results [7]. However, its measurements are affected by distortion produced in the sonic signal by rainfall, fog, insects, and dirt. In addition, full knowledge about the optimal system set up and EC raw data handling is still under development [8]. However, weighing lysimeter is a reliable method for ET measurements but it is seldom used outside of experimental stations [9]. The Bowen Ratio (BR) method requires extensive fetch and responsiveness to the biases of instrument used for estimating the air temperature and water vapour pressure at two levels [10]. The scintillometer method is a high-cost method, based on Monin-Obukhov similarity theory (MOST) and high skills are required for correct operation. In addition, its estimations are disrupted by optical interception of rainfall, insects, frost, and vertical air temperature to differentiate between the ascending and descending directions of sensible heat flux (H) [11]. But there are many micrometeorological methods available for the ET estimation [12–16]. Since the EC method is not available for farmers due to its high cost and complex operation, an economical and simple technique is required to measure ET at farm level. The surface renewal (SR) method has been considered as a feasible supplement of the EC method. The SR method has drawn more attention to estimate ET, due to its technical simplicity and high reliability.

In the present work, a comprehensive review of the SR method is presented. The parameters affecting the results of SR are provided and detailed comparisons among different methods are discussed. The advantages and disadvantages of each method are also provided. This review article aims to provide a broad outlook for the researchers working on ET estimation using the SR method.

2. History of SR

The SR concept originated from chemical engineering and was developed by Higbie in 1935 to examine the transport of heat between gas and liquid [17]. The SR method is based on the theory that an air parcel quickly moves to the surface and remains connected with the surface for a period of time, after which it is cooled due to the sensible heat exchange between the air and plant canopy elements. The air parcel then moves upwards and is renewed by another parcel that moves towards the surface [8, 18].

In 1955, Danckwerts presented the concept of a variable time interval. Later, the concept that there was a quiescent liquid layer at the surface separating the renewed fluid elemental volumes and the surface was added [19]. Dobbins (1956) and Torr et al. (1958) added finite elemental volume to the SR method. In 1961, eddy statistics were introduced to the SR method by Perlmutter [18]. Afterwards, further development included extracting the method from the fluid element volumes reaching arbitrary distances from the surface for irregular gaps [20]. There were further developments and research was published in this field during subsequent years when research was performed to produce some modifications in the original technique. This work was subsequently also published, including transient flow study and momentum transfer applications [21, 22]. Additional research work was published on the operation and development of the SR method [23–38]. The engineering method has also been applied to the ocean surface-atmosphere interface [39–42]. From the 1990s, the SR method has been adapted for micrometeorology and research was undertaken on the estimation of H by using the SR method [43, 44]. However, development of the SR method continues, especially for making it more reliable without the need for calibration. Currently, the SR method is considered the best substitute for EC [45].

3. Mechanism of SR for ET Estimation

ET is the combination of evaporation and transpiration of water vapour evaporated from the soil and the plant canopy to the atmosphere. Evaporation is the movement of water to the air from plant canopy or soil to the atmosphere. However, transpiration includes the water within the plant canopy and the amount of water lost from the plant through stomata of its leaves. ET is a crucial part of irrigation water management strategies. Hence, the correct estimation of ET in agriculture is important. Some of the methods used to calculate ET are based on the energy balance equation, which describes the energy fluxes over a control volume that includes the vegetation system. The shortened energy balance equation under steady conditions is given as follows:

$$LE = Rn - G - H, \tag{1}$$

where Rn is the net irradiance, G is the soil heat flux, H is the sensible heat flux, and LE is the latent heat flux. LE is the total energy flux removed from the control volume through the evaporation of water and is obtained by evaporation rate and latent heat of vaporization of water. Latent energy flux can be estimated directly or as a residual of the energy balance equation. Net irradiance (Rn) is the difference between total (longwave and shortwave) incoming and outgoing radiations between plant canopy and atmosphere. Solar radiation is a substantial energy source accessible at the surface of the earth for heating soil and air [59]. The estimation of Rn is crucial in the SR process for the correct estimation of ET. There are many commercial products for measuring Rn (i.e., Kipp & Zonen NR-Lite, REBS, and Hukseflux model NR01) [45, 60–62]. G is the rate of heat transfer per unit ground surface. It is measured using soil heat flux plates and temperature sensors. These plates comprise thermopiles that measure the temperature gradient across the plate material having a known thermal conductivity to estimate G. Its calculation is important in the estimation of ET in the SR process. Different models of soil heat flux plate are available for the estimation of G. The SR method is established on the turbulent exchange of sensible heat flux between plant canopy and atmosphere, caused by the instantaneous replacement of

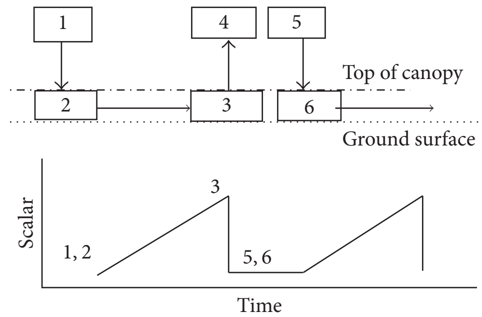

Figure 1: Development of ramps under unstable conditions traveling on an air parcel and the parcel is warmed by plant canopy elements [18].

an air parcel interacting with the surface (Figure 1). The air parcel exchanges energy between air and canopy elements; then the parcel is detached from the surface and is replaced by a new air parcel. Thus, understanding the features of this turbulence mechanism is vital for correct operation and analysis of this method [17, 58, 63, 64].

The SR method for estimation of fluxes from plant canopies involves high-frequency (2 to 10 Hz) air temperature measurements using a miniature fine-wire thermocouple. The signal of air temperature displays well-managed coherent structures that resemble ramp events [43, 65–67]. The coherent structures are responsible for exchanging mass, energy, momentum, and other scalar fluxes [67, 68]. In the SR method, the estimation of H is based on high-frequency measurements of air temperature and LE is obtained as the residual of the shortened energy balance equation. There are three methods for the calculation of H using the SR method: the classical SR method is based on the structure-function analysis presented by ATTA (1977) [69]. Other methods are the SR method with finite micro front period and empirical SR analysis method based on MOST [54, 70].

4. H Calculation with SR

H is the amount of heat flux exchanged between the soil or plant canopy and the atmosphere by conduction and convection as a result of temperature differences between ground surface and atmosphere. There are several micrometeorological techniques for estimation of H, including BR, EC, OS, FV, and the SR method. The SR method is based on examining the energy budget of air parcels or coherent structures that reside ephemerally within the crop canopy during the turbulent exchange process [63]. The exchange of air parcels between surface and atmosphere is manifested as ramp-like shapes in turbulent temperature time series data; the amplitude and period of the ramps are used to calculate H using the following equation:

$$H = \alpha H' = \alpha z \left(\rho cp\right) \frac{a}{\tau}, \quad (2)$$

where α is the calibration factor, z is the measurement height (m), a is the ramp amplitude (K), τ is the ramp period (s), H' is uncalibrated sensible heat flux, ρ is air density, and c_p is the specific heat capacity of air. SR calculations require calibration against an independent flux measurement method (i.e., EC). The calibration factor (α) is obtained as the slope of the least-squares linear regression forced through the origin, between noncalibrated SR data and EC measurements of H; its value depends on measurement height, canopy height, canopy architecture, atmospheric stability, turbulence characteristics, and sensor dynamic response characteristics [18, 63]. The Van Atta structure-function analysis method is used to calculate the ramp amplitude and period from the high-frequency air temperature signal [54, 63]. The structure-function analysis is calculated by the following equation:

$$\overline{S^n(r)} = \frac{1}{m-j} \sum_{k=1}^{m-j} \left[\left(T_k - T_{k-j}\right)^n\right], \quad (3)$$

where $S^n(r)$ is the nth-order structure function, m is total number of data points, and j is lag between sampling points. T_k is the kth element in the calculated temperature data. The time lag (r) is calculated as the sample lag divided by the sampling frequency ($r = j/f$). The structure-function values are used to determine the coefficients in the following cubic polynomial:

$$a^3 + pa + q = 0, \quad (4)$$

where p is obtained:

$$p = \left[10S_{(r)}^2 - \frac{S_{(r)}^5}{S_{(r)}^3}\right]; \quad (5)$$

and q is obtained as

$$q = 10S_{(r)}^3. \quad (6)$$

These equations can be solved analytically to obtain the ramp amplitude. The ramp period is evaluated from the ramp amplitude, time lag, and third-order structure function using the following equation:

$$\tau = -\frac{a_{(r)}^3}{S_{(r)}^3}. \quad (7)$$

Finally, H is obtained as follows:

$$H = \alpha H', \quad (8)$$

where H' is uncalibrated sensible heat flux measured by SR and H is sensible heat flux measured with EC. α is the calibration factor estimated by calibrating the SR method against any independent method (i.e., EC and BR).

5. Parameters Affecting SR

The SR method is an indirect method of ET estimation. The parameters affecting the results of the SR method are explained below.

Table 1: Effect of different parameters on SR.

Crop	Sensor height (m)	Sensor diameter (μm)	Sampling frequency (Hz)	Calibration factor (α)	Reference (year)
Bare soil	—	12.7, 25.4, 76.2	8	0.90, 1.04, 1.88	1998 [46]
Open water	1.0, 1.3, 1.9, 2.6	75	10	0.2, 0.25	2010 [47]
Irrigated pasture (tall fescue)	0.75 (0.6)	75	4	0.35 (0.4)	2008 [48]
Sugarcane	0.2, 0.5, 0.75, 1.5	75	10	0.55 to 0.66	2010 [49]
Flood-irrigation pecan	−3.7, 0	—	4	1.1 ($z = d$), 0.5 ($z = h$)	2007 [6]
Bare soil	0.5, 1.0, 1.5, 2.0	13	10	0.38, 0.39, 0.42, 0.46	2012 [50]
Rice	0.3, 0.6, 0.7, 0.8, 0.9, 1.0, 1.4, 1.45, 1.55, 1.7	76	10	1.0	2013 [51]
Lagoon	0.9, 1.1, 1.4	76	8	1.0	2002 [52]
Grapevine	2.0, 2.3, 2.6, 2.9	76	8	0.88, 0.81, 0.76, 0.66	2000 [53]
Sorghum	0.7, 1.0, 1.3	76	8	1.0	1997 [54]
Wheat	0.7, 1.0, 1.3	76	8	0.5	1997 [54]
Grass	0.3, 0.6, 0.9, 1.2	76	8	—	2014 [55]
Vineyard	0.5, 1, 1.5	76	10	0.67–0.93	2015 [56]
Tomato	0.5, 1.0, 1.5, 2.0, 2.5	75.2	10	1.82	2015 [57]
Grass	1, 1.43, 1.86	76	10	0.66	1997 [58]

5.1. Measurement Height and Fetch. For the correct estimation of ET, by using the SR method, the correct height and fetch are important parameters for measurements. Castellví and Snyder suggested that sensors can be deployed at any height near to plant canopy surface and the height will influence the fetch requirement directly for the flux estimation with the SR method [45]. Castellví verified the need for establishing a footprint model for the SR method showing that fetch requirements are almost the same as for the EC method [71]. Previous studies on the effect of different parameters on SR estimations are presented in Table 1.

5.2. Sensor Diameter and Sampling Frequency. The SR method is based on high-frequency air temperature measurements using a miniature temperature sensor, usually a thermocouple (TC). For correct estimation of H, the size and type of TC and sampling frequency are crucial elements. Most measurements reported in the literature were taken in the frequency range of 1 to 10 Hz (Table 1) and in some cases the data were analyzed at lower frequencies (down to 1 Hz) to simulate low-frequency data acquisition. Many researchers suggested that the frequency of 10 Hz is appropriate for the SR method [9]. Thermocouple sensors are available in different types (i.e., K, T, and E) and diameters (12.2, 25.2, and 76.2 μm). Brotzge et al. presented a reduced magnitude of SR flux estimation when the high-frequency air temperature was collected using 76 and 25 μm TC as compared to 13 μm [45, 47]. Measurement of air temperature through the SR method using TC of 76 μm is widely accepted [46].

5.3. Calibration Factor (α). For the SR method, the calibration factor plays an important role in the correct estimation of H. Accurate data for α is still missing, especially in nighttime data under stable conditions. Estimated values of α calculated at the top of various canopies and different frequencies (i.e., 8–10 Hz) were estimated at approximately 0.23 for citrus and 1.88 for short grass [53, 72]. For the calibration of H measured by the SR method, different α values are sometimes used for stable and unstable conditions. Spano et al. performed experiments under stable and unstable conditions and the results justified the separation of α between stable and unstable conditions [53]. Usually α for unstable conditions (daytime) was larger than that obtained for stable conditions [57]. Previous studies on the effect of α value for different measuring heights are shown in Table 1.

6. SR Application for ET Estimation

The SR method is relatively inexpensive and fairly simple to operate and analyze. There are other micrometeorological methods available for ET estimation (i.e., BR, weighing lysimeter, and EC). This section compares SR with the other methods.

6.1. SR versus Eddy Covariance. The SR method is relatively new as compared to the EC method. EC directly measures ET by measuring water vapour exchange between the atmosphere and plant canopy. It is widely used for ET measurement due to the ability to produce direct results. However, EC is very expensive and its results could be affected by distortion produced in the sonic signal by rainfall, fog, insects, and dirt. As compared to EC, the SR method is inexpensive and uncomplicated. The SR method can produce good results inexpensively by using high-frequency air temperature signal. Some studies that compared these two methods are discussed. Spano et al. conducted experiments over grass of about 0.1 m using SR and EC and showed favourable agreement against the EC method. Best results of $R^2 = 0.93$ were obtained at 0.75 time lag (r) and height of 6 m [58]. Spano et al. performed experiments in three different fields (dense, tall, and short canopies) in vineyards for testing the reliability of SR. Results indicated good estimations ($R^2 = 0.80$) at 2 m height for 33 data points at $\alpha = 0.5$ and $\alpha = 0.1$, respectively. The estimation of H at normal height and under plant canopy was conducted (13) and for measurements at the canopy top by Tillman using the following equation:

$$H_T = \rho c_P \left[\left(\frac{\sigma_T}{C_1} \right)^3 \frac{kgz}{\overline{T}} \right]^{1/2}, \tag{9}$$

where $C_1 = 0.95$, k is von Karman constant ($k = 0.41$), g is acceleration of gravity, T is mean air temperature, and σ_T is the standard deviation of the temperature. Further, for all the experiments performed at any height, the estimation of H was under 45 $\mathrm{Wm^{-2}}$, which presents good estimation [53]. Zapata et al. estimated long-term ET of playa and margins of an endorheic salty lagoon using EC and SR. The estimation of H was undertaken using the following equation [63]:

$$H_{\mathrm{SR}} = \alpha \rho c_p \frac{\alpha}{l + s} z_m, \tag{10}$$

where z_m is the measurement height, assuming $\alpha = 1$ for the measurements obtained above the plant canopy. Results indicated good agreement between the measured values of EC and SR irrespective of measurement height; best results were obtained at $z = 0.9$ m and all regressions had $R^2 > 0.8$ [52]. Simmons et al. performed experiments over tall pecan canopies using SR and EC; for the estimation of H, (11) and (12) were used for EC and SR methods, respectively:

$$H_{\mathrm{EC}} = \rho c_p \left(\overline{w'T'} \right), \tag{11}$$

$$H = \rho c_p \frac{A_{T2}}{\tau_{T2}} z, \tag{12}$$

where T' are the sonic temperature fluctuations and w' are the fluctuations of vertical wind speed. Results showed good agreement against EC over all heights, especially at 7 m. Results were more reliable during daytime [6]. Snyder et al. estimated ET over irrigated pasture for short grass using SR. The estimation of uncalibrated H was performed the following equation:

$$H' = \rho c_p \left(\frac{a}{d + s} \right) z, \tag{13}$$

where $d + s$ is inverse ramp frequency. Results indicated good estimation for the whole cropping season [48]. Drexler et al. performed experiments for the evaluation of the SR method over rangeland grass using the SR and EC methods. For the estimated values of ET, the SR method presented good agreement against EC; RMSE was 1.5–1.7 $\mathrm{MJm^{-2}day^{-1}}$. Results indicated that EC closure performs well under humid conditions, while SR could not perform well under the same conditions, for SR fluxes determined under stable conditions were too small to measure. It is concluded that SR can perform well compared to the estimations of EC with simple and low-cost instrumentation as compared to EC [73]. Castellví conducted experiments for the evaluation of SR and EC under stable and unstable conditions. Estimation of H was performed as in Castellví's work for the roughness sublayer [9]. Results indicated good estimation for unstable conditions with RMSE = 57 $\mathrm{Wm^{-2}}$. For stable conditions, the fluxes were too small to measure. Results concluded that SR is a good low-cost replacement for EC [8]. Castellví et al. performed an experiment over a peach orchard for examining the reliability of the SR versus EC method. H was estimated using the classical SR approach as follows:

$$H = \rho c_p (\alpha z) \frac{A}{\tau}. \tag{14}$$

Results indicated $R^2 = 0.85$ for stable conditions, $R^2 = 0.92$ for unstable conditions, and $R^2 = 0.95$ for all data. The authors concluded that SR can perform well under unstable conditions and can be used inexpensively as a replacement for EC [45]. Castellvi et al. derived a new technique for SR estimation over a vineyard canopy; calibration was performed against the EC method. The estimation of H was performed by adding a new parameter from the following equation [74]:

$$u_* = 0.4\sigma_u, \tag{15}$$

where u_* is the friction velocity and σ_u is the standard deviation of horizontal velocity. Regardless of stability conditions, the SR method produced RMSE = 14 $\mathrm{W\,m^{-2}}$, which proposed an affordable alternative to EC for the estimation of ET in regions influenced by advection of H [75]. Mengistu and Savage estimated ET of a small reservoir using the SR and EC at different heights. Chen et al. produced a new SR model based on the formation of air temperature ramps for the estimation of H from high-frequency air temperature measurements using cubic and the additional measurement of frictional velocity. Accordingly, the estimation of H for roughness and sublayers was done using the following equation [76]:

$$H = -\alpha \beta^{2/3} \gamma \rho c_\rho \left[\frac{S^3_{(r_m)}}{r_m} \right]^{1/3} u^{*(2/3)} \frac{z}{(z - d)^{2/3}}, \tag{16}$$

where $\alpha\beta^{2/3}\gamma$ is combined empirical coefficient, $S^3_{(r_m)}$ is 3rd-order structure function, r_m is the time lag, and $z - d$ is the zero-plain displacement. The SR method produced a good estimation of ET of approximately 2.70 mm, while overall ET of that region was approximately 1.0 to 3.9 mm. Therefore, their results presented good estimation of ET using SR [47]. Castellví introduced a new model of the SR method, which does not require calibration by inducting the measurement of horizontal wind speed. An experiment was conducted over a mature orange orchard to assess the performance of SR. Two models of SR were used in the analysis, one with high-frequency air temperature and the other with additional wind speed at different heights; the estimation of H was conducted using the Castellví procedure [9]. Results indicated good agreement with EC data with $R^2 = 0.91$ [77]. Shapland et al. estimated ET over a level vineyard using the SR and EC methods. Estimation of H was conducted using (13). Results showed $R^2 = 0.56$ against EC, suggesting that further development of SR over level vineyard is required [78]. Rosa et al. tested the different frequency and height when estimating ET of a tomato crop by SR and EC. Estimation of H was conducted using Spano et al.'s procedure [53]. Results indicated good correlation between SR and EC, $R^2 = 0.86$, and RMSE = 29.57 W m^{-2} [79]. Moratiel and Martínez-Cob estimated ET over a rice crop under sprinkler irrigation for the entire cropping season, and the estimation of H was performed according to the research by Paw U et al. [18, 51]. Suvocarev et al. conducted experiments for two different models of SR for estimation of H over a heterogeneous crop surface. Calculations of H for two scales using the ATTA analysis at normal height and above due to gradual rise produce in the ramp were measured using (17) and (18), respectively:

$$H = \rho c_p \frac{A_{T2}}{\tau_{T2}} z, \tag{17}$$

$$H_{\mathrm{SRCas}} = \rho_a \alpha_T c_p \frac{A_T}{\tau_T} z. \tag{18}$$

Results indicated both first and second scales as $R^2 = 0.87$ and $R^2 = 0.80$, respectively. For the early stage of a peach, $R^2 = 0.96$ for EC and $R^2 = 0.80$ for SR were produced. It is concluded that SR can perform similarly to EC [80]. Mekhnmandarov et al. tested the application of the SR method under screen house conditions for pepper and banana fields. For the estimation of H, Paw U et al.'s method was used [18]. Results demonstrated that $R^2 = 0.93$ and 0.65 above the shading and insect-proof screens, respectively [57]. Rosa et al. conducted an experiment over two different cropping seasons for a cotton crop for H estimation using SR and EC. For the estimation of H, Spano et al.'s method was used [53]. Results indicated that a deviation of about 7% was reported between total calculated ET from both methods and concluded that SR could produce a good estimation of ET [56]. Undoubtedly, according to all mentioned experiments, it has been proven that the SR method inexpensively demonstrates performance efficiency under different climatic conditions and surfaces as compared to the EC method.

6.2. SR versus Monin and Obukhov Similarity Theory (MOST). In 1954, Monin and Obukhov derived two scaling parameters for the structure of turbulence in the surface layer, which is independent of height [81]. Optical scintillometer (OS) based on the MOST theory is widely used for the estimation of H. This method is costly and difficult to handle and additional skills are required for operation. In addition, estimation of the OS could be distorted by rainfall, frost, and vertical air temperature [11]. SR is a relatively inexpensive and simple technique as compared to MOST. Many research experiments were conducted for the evaluation of the SR method as compared to MOST on the same experimental fields. Castellví conducted the experiment for the estimation of H over an orange orchard using two methods, one with the classical SR (called SR1) and the other with SR that was modified using MOST (SR2). The estimation of H was performed using the following equation [9]:

$$H = \rho c_p (\alpha z) \frac{A}{\tau} \begin{cases} \text{methodSR1: } \alpha = \text{constant}, & \text{for } hc < z \\ \text{methodSR2: } \alpha = \left[\dfrac{k}{\pi} \dfrac{(z^* - d)}{z^2} \tau u_* \phi^{-1}(\zeta) \right]^{1/2}, & hc < z < z^*, \end{cases} \tag{19}$$

where τ is the inverse ramp frequency and ζ is stability parameter. Results indicated that, for SR, the RMSE was between 39 and 52 W m^{-2} and for SR2 the RMSE was between 56 and 77 W m^{-2} [77]. Savage conducted experiments over mesic grassland for the estimation of ET and H using SR and OS; the estimation of H using OS is as follows:

$$H = \rho c_p u_* T_*, \tag{20}$$

where T_* is temperature scaling parameter (K). A simple Excel iterative procedure was applied for estimating ET using surface temperature. Results showed that subhourly measurements of OS for H estimation over a path length of 100 m produced a 4% accuracy of H. Overall, MOST performed well and demonstrated good agreement with the calculations of SR. SR performed better under unstable as compared to stable conditions [82]. Castellvi presented a new technique for the estimation of H using MOST by introducing calibration factor β for half-hourly samples and presented a new technique for the estimation of H under slightly unstable conditions in both roughness and inertial sublayer, respectively:

$$\begin{aligned} H &= 2.4\rho c_p \left(\frac{g}{T}\right)^{1/5} \frac{\left[k(z-d)^{4/5}\right]}{\pi^{3/5}} \left(-\gamma^3 \frac{S^3{}_{(rx)}}{r_x}\right)^{3/5} \\ &\quad \cdot A^{-3/5} \quad \text{if } (z-d) > z^* \\ H &= 2.4\rho c_p \left(\frac{g}{T}\right)^{1/5} k^{4/5} \left(\frac{z^*}{\pi}\right)^{3/5} z^{1/5} \left(-\gamma^3 \frac{S^3{}_{(rx)}}{r_x}\right)^{3/5} \\ &\quad \cdot A^{-3/5} \quad \text{if } h \le z-d \le z^*, \end{aligned} \tag{21}$$

where T is air temperature. The test was performed over the canopies where fetch requirements and the surface cover were not satisfactory. Results indicated that the estimation of H by a new technique, which is exempted from the calibration, performed very well under both stable and unstable conditions [9]. Castellví used two techniques, one in the inertial sublayer and another in the roughness, and testing was done on grass, rangeland grass, wheat, grape vineyard, and olive garden. MOST performed well in both layers above the plant canopy. Estimation of H was performed for roughness and inertial sublayer using (22) and (23), respectively:

$$H = \rho c_p \left(0.8 (kg)^{1/2}\right) \frac{(z-d)}{T^{1/2}} C_{tt}^{3/4} \quad \zeta \ll -0.14 \tag{22}$$

$$H = \rho c_p \left(1.08 (kg)^{1/2}\right) \left(\frac{z-d}{T}\right)^{1/2} \sigma_T^{3/2} \qquad \zeta < -0.04, \tag{23}$$

where σ_T is air temperature standard deviation. Results indicated $R^2 = 0.9$ and $R^2 = 0.7$ for inertial sublayer and roughness, respectively, and concluded that this technique could perform well over long cropping periods [83]. Castellví et al. presented a new equation for the estimation of H, using other findings to bypass the errors [9, 70].

$$H_{\text{SR}} = \rho c_p k \beta (z) \phi_h^{-1} \left(\frac{z}{L}\right) u_* A_{(z)}, \tag{24}$$

where β is the semiempirical parameter. Under natural conditions, it will remain constant over homogeneous and heterogeneous canopies. Under convective and close to natural conditions, it is expected to remain constant; estimation of H was performed as follows:

$$H = -\rho c_p k \alpha (z) \phi_h^{-1} \left(\frac{z}{L}\right) u^* \left(T_c - T_{(z)}\right), \tag{25}$$

where $\alpha_{(z)} = \beta / s_{(z)}$ because λ values were obtained using Chen's model. It is recommended to determine $\alpha_{(z)}$. This technique showed the really good estimation of H over bare soil and sparse vegetation [9]. Castellvi performed experiments for the estimation of H over grass and produced a new technique by measuring extra wind speed. For the estimation of H, (2) was used, and for explaining the half-hourly variability α in half-hourly basis in the inertial sublayer, the flux gradient relationship $H = -\rho c_p K_h (\partial \overline{T} / \partial z)$ was developed using (2) and the estimation of H determination is as follows:

$$H = \rho c_p \sqrt{\frac{K_h}{\tau \pi}} A, \tag{26}$$

where K_h is the eddy diffusivity. This new technique performed well in unstable as compared to stable conditions ($0.78 \leq R^2 \leq 0.90$) [83]. These experiments indicated the introduction of MOST in the SR method for the correct estimation of H, which consequently produced ET with the energy balance equation. The introduction of MOST to the classical SR method performed well on different surfaces and under different climatic conditions. It is complex but is becoming more widely used as this technique is exempted from calibration, which was a disadvantage of the SR method. However, this new method performs well but its reliability needs to be verified for the whole cropping season under different climatic conditions.

6.3. SR versus Flux Variance Method. Wyngaard et al. (1971) and Tillman (1972) introduced the Flux Variance method that is based on Monin Obukhov Similarity theory (MOST) and measurements of scalar fluxes [81, 84]. The FV method allows the turbulent scalar fluxes to be calculated from measurements of the scalar at a height above the canopy surface. The FV method is less expensive and requires relatively lower power as compared to most of other micrometeorological methods for the estimation of ET. The FV method has been applied and testified at different surface types, homogeneous and heterogeneous surfaces, and different atmospheric stability conditions by different researchers; some of them are described here. Castellví et al. conducted experiments over a heterogeneous canopy under windy and semiarid conditions. In this study, the estimation of H was performed under slightly unstable conditions as follows [84]:

$$H = \rho c_p \left(\frac{\sigma_T}{C_1}\right)^{3/2} \left[\frac{kg (z-d)}{T}\right]^{1/2}. \tag{27}$$

Results demonstrated that SR produced good results under both stable and unstable conditions. FV produced good estimations in unstable conditions but performed poorly under stable conditions [85]. French and Alfieri conducted an experiment over two cotton crop fields for testing the reliability of SR and FV and calibration was done against EC. In this study, H was determined by using the model in (28) proposed by Tillman [84]:

$$H = \rho c_p u_* \left(\frac{\sigma_T}{C_1}\right) \left[C_2 - \zeta\right]^{-1/3}. \tag{28}$$

Results indicated that the SR method performed well during the unstable condition as compared to the FV method [86]. The FV method produced good results under unstable conditions but performed poorly under stable conditions. Results indicated that SR is relatively superior for the estimation of ET under both stable and unstable conditions as compared to the FV method at various scales.

6.4. SR versus Bowen Ratio (BR). Bowen Ratio (BR) method is widely used for the measurement in different climatic conditions, but the main difficulty in using BR for the estimation of ET is that it requires extensive fetch and cannot perform well under dense crops. It is also very responsive to the sensors used for the measurement of water vapour pressure and air temperature profile difference [10].

6.5. SR versus Weighing Lysimeter. Weighing lysimeter is long-standing method used for the estimation of ET. It can produce good results under different conditions, but the main difficulty is that the lysimeter represents only a single plant or few plants and not the entire canopy. Also, the lysimeter modifies the conditions of the soil-plant environment; hence, its relation to actual field conditions is sometimes questionable. Many researchers compare the results of the weighing lysimeter with the SR method, some of which are discussed here. Sanden et al. performed an experiment in two different plots of alfalfa with and without irrigation using the

SR method and compared the results against the weighing lysimeter. Results indicated good agreement between the SR and weighing lysimeter with $R^2 = 0.956$ [87]. Moratiel et al. estimated ET over a rice crop under sprinkler irrigation system for entire cropping season using SR and a weighing lysimeter. Results indicated $R^2 = 0.783$ and $R^2 = 0.996$ for weekly and cumulative ET, respectively. It is concluded that the SR method could be a good replacement for a lysimeter and can produce results similar to the lysimeter [51]. Castellví and Snyder performed experiments over a grass field using the SR method which was compared with the lysimeter regardless of weather and time of day. Results demonstrated good agreement between SR and the lysimeter of approximately $R^2 = 0.97$ [88]. Shapland et al. presented an open turnkey data logger program for the flux measurement for SR and weighing lysimeter over a wheat canopy for short periods. Results indicated cumulative ET values from the flux tower and the logger program indicated good agreement with the measurements from the weighing lysimeter [89]. The weighing lysimeter performed well for the entire cropping season but the main difficulty for the lysimeter is its operation complexity and cost. Therefore, lysimeters are seldom used outside research stations.

7. Advantages and Disadvantages of SR

At different scales, SR offers numerous pros and cons; its advantages are that it is relatively inexpensive and easily operated. It is less dependent on fetch requirement and can produce comparatively closer results to EC inexpensively [45]. It is useful for rough or nonhomogenous surfaces and can produce good results on hilly fields. The SR method can perform well for surfaces with dense canopies [89]. Measurements are relatively easy and missing data due to damage of TC can be avoided by using additional TCs. In the SR method, calculations can be exempted from calibration by measuring horizontal wind speed. This technique can remove the difficulty of calibration from SR [8]. In SR analysis, the calculations are relatively simple; therefore the experiment could be performed continually for obtaining repetitions of results inexpensively. Major drawbacks of SR have been documented in various studies; the method cannot produce good results in high humidity conditions (i.e., rainfall, snow, and frost) [8]. It is based on high-frequency air temperature measurements with a miniature (TC). These TCs are prone to damage in high wind conditions. The SR method needs more attention and care during experiments. The actual accuracy of this method in estimating ET depends upon the results obtained from the calculations of Rn and G.

8. Prospective Study on SR

SR is a relatively inexpensive method in the field of micrometeorology for the estimation of ET. Since this method is based on the theory of short-term heat transfer between the plant canopies and surface boundary layer, it is valid in both the roughness and inertial sublayers. The classical SR method is an inexpensive alternative for the estimation of H; however, this method required calibration against any independent method (i.e., EC and BR). Two calibration factors are recommended for the correct estimation of H for stable and unstable conditions, respectively.

The SR method can be used for the estimation of water vapour flux and other scalars directly. In the surface layer, turbulent coherent structures exchange scalars between plant canopy surface and the atmosphere; by estimating the characteristics of these ramp structures, the exchange rates can be determined. The SR method showed satisfactory performance for surfaces ranging from tall canopies to bare soil. Castellví et al. derived a new model for the estimation of H with SR by including horizontal wind speed and this method is exempted from calibration against any independent method [8]. This modified SR method produced good results under different conditions; a simple data logger program can be used for easy data collection in the field. The SR method is convenient for ET estimation for short, dense, or well-irrigated vegetation, which provides a good approach for irrigation management.

The SR method can be applied to other fluxes (i.e., CO_2, water vapour pressure, and other gas concentrations). Hence, research should focus on the application of the SR method for the estimation of other scalar fluxes. SR application for the determination of LE is also a significant aspect in future studies. The new model of the SR method exempted from calibration is still new and its reliability should be validated on different surfaces and under different climatic conditions. The SR method should be used for the estimation of ET of different crops for an entire cropping season for verifying the reliability of TC for a longer period of time. Studies are necessary to investigate the performance of TC under frost conditions or at low temperature. Research is necessary to overcome the problem of missing data in the rainy season so that the SR method can perform well under wet conditions. The main focus should be on the development of SR to investigate its effectiveness under stable conditions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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