Journal of Hydrology 410 (2011) 84–91

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Comparative analysis of two polyethylene foil materials for dew harvesting in a semi-arid climate

J.F. Maestre-Valero *, V. Martínez-Alvarez, A. Baille, B. Martín-Górriz, B. Gallego-Elvira

Universidad Politécnica de Cartagena, Escuela Técnica Superior de Ingeniería Agronómica, Paseo Alfonso XIII 48, 30203 Cartagena, Spain

ARTICLE INFO

Article history:
Received 5 April 2011
Received in revised form 23 August 2011
Accepted 10 September 2011
Available online 19 September 2011
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Efrat Morin, Associate Editor

Keywords:
Water condensers
Water harvesting
Dew collection
Infra-red emissivity
Dew applications

SUMMARY

This paper analyses the dew collection performance of two polyethylene (PE) foils in a semi-arid region (Southern Spain). The dew collecting devices consisted of two commercial passive radiative dew condensers (RDCs) of 1 m^2 tilted to 30°. They were fitted with two different high-emissivity PE foils: a white hydrophilic foil (WSF) recommended as standard for dew recovery comparisons by the International Organization for Dew Utilization (OPUR), and a low-cost black PE foil (BF) widely used for mulching in horticulture. Dew yield, foil surface temperature and meteorological variables (air temperature, relative humidity, downward long wave radiation and wind speed) were recorded hourly during a 1-year period from May-2009 to May-2010. The spectral emissivity of the foils was determined in laboratory in the range 2.5–25 μm and the radiance-weighed values were calculated over different intervals, indicating that BF emitted more than WSF, especially in the range 2.5–7 μm. Dew yield was well correlated with the air relative humidity and foil net radiation in both foils and was hardly detected when the relative humidity was lower than 75% or the wind speed higher than 1.5 m s^{-1}. WSF was more sensitive to dew formation due to its hydrophilic properties, registering more dewy nights (175) than BF (163) while the annual cumulative dew yield for BF was higher (20.76 mm) than for WSF (17.36 mm) due to the higher emissivity and emitted radiance of BF. These results suggested that increasing the surface emissivity over the whole IR spectrum could be more effective for improving RDC yield performances than increasing the surface hydrophilic properties. On a practical point of view, BF could be considered as a suitable material for large scale RDCs, as in our study it presented several advantages over the reference material, such as higher dew collection performance, longer lifespan and much lower cost.

1. Introduction

Dew is atmospheric humidity that is transformed into liquid water by passive radiative cooling (Monteith, 1957; Beysens, 1995; Agam and Berliner, 2006). Under natural conditions, this potential water source can be widely used by plants and animals in dry environments and can supply enough moisture to microorganisms for survival (Steinberger et al., 1989; Kidron et al., 2002). Dew collection by means of manufactured structures could serve as a welcome supplementary source of water when other sources, such as rain and groundwater are very scarce. Besides, dew could be used as potable water for human consumption in regions where the water accessibility and supply becomes difficult (Muselli et al., 2006a; Lekouch et al., 2011), such as semi-arid and arid geographical settings and small islands in developing countries (Beysens et al., 2007; Sharan, 2007a).

The essential role of dew as a water source in arid environments, ecosystems and agrosystems largely explains the increasing interest among scientists and engineers in studying the dew formation phenomenon. The presence/absence of dew can be readily detected by means of wetness sensors (Richards, 2009). The quantification of dew yield on different types of surface can be carried out by means of a wide range of methods, such as absorbent material or cloth plates (Kidron, 2000), microlysimeters (Jacobs et al., 2002), micrometeorological techniques such as the Bowen ratio energy balance or the eddy-covariance technique (Vermeulen et al., 1997; Moro et al., 2007), and dew-specific collectors, called passive 'radiative dew condensers' (RDCs, Beysens et al., 2005).

Among all these methods, RDCs are likely the most suitable techniques to be used at engineering applications, as they allow to assess the performance of different types of foils and supporting structures (shape, tilt, etc.). The International Organization for Dew Utilization (OPUR; http://www.opur.fr/) has widely standardized the characterization of dew collection by establishing the methodology, instrumentation and data obtained from in-field experimental test studies. This organization recommends the use of a standard material which is made of a special white low-density polyethylene (PE) foil, with 5% volume of TiO_2 microspheres (diameter 0.19 μm) and 2% volume of $BaSO_4$ microspheres (diameter 0.8 μm) embedded in it. This material provides hydrophilic

* Corresponding author. Tel.: +34 968 32 70 52; fax: +34 968 32 54 33.
E-mail address: josef.maestre@upct.es (J.F. Maestre-Valero).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2011.09.012

properties that low the nucleation barrier at the onset of the condensation process together with a high emissivity in the near infrared (7–14 μm); two important features that favor dew formation. More information on this material can be found in Nilsson (1994). From here on, this specially designed white foil is named WSF (White Standard Foil).

Several recent investigations aimed to assess the potential for dew harvesting using the standard foil have been reported. Muselli et al. (2002) tested a 30 m^2 RDC near Ajaccio (Corsica, France), measuring 214 dewy nights over an observation period of 478 days, with an average of 0.12 mm per dewy night and a maximum daily yield of 0.38 mm. In a posterior study at the same site (Muselli et al., 2006a), similar dew yield were obtained (average of 0.13 mm per dewy day). Jacobs et al. (2008) compared two types of RDCs fitted with WSF, one being a 1 m^2 insulated planar dew condenser set at a 30° angle from horizontal, and the other presenting an inverted-pyramid shape. Recently, Muselli et al. (2009) studied the dew yield at the Dalmatian Coast with two 1 m^2 RDCs fitted with WSF, concluding that it could be worthwhile to rehabilitate the numerous deserted rain collectors (impluviums) existing in the region for the objective of dew harvesting.

The standard WSF is currently rather expensive (8 \$ m^{-2}) since it is generally manufactured for research purposes. A trend to use low-cost collector foils with similar performances would be feasible for large scale dew recovery systems, where water can be harvested for domestic and rural activities at the individual farm or village scale. Some rural development projects, especially in India (Sharan, 2007a), tried to promote rain and dew recollection over large areas, by covering the soil of gentle-slop terrain with PE foils. In such large scale systems, the covering material should be of low cost, resistant to weathering, tensile and friction forces, and easily available to farmers of developing countries. A suitable choice might be the installation of black PE foils that are widely used in agriculture as soil mulching for weed control, as such films respond to the above criteria. However, the potential for dew recovery of such films is not known, and need to be assessed before recommending them for dew harvesting.

The main objectives of this study were (1) to compare the properties and dew recovery performances of a low-cost black PE foil with respect to the standard white PE foil, (2) to analyze the physical factors driving dew formation to contribute to a better knowledge of the dew formation process in semi-arid regions and (3) to assess the potential of dew recovery in a semi-arid region of South Spain, where techniques of dew harvesting could help in mitigating the impact of extreme drought events.

2. Materials and methods

2.1. Site and dew water condensers

The experimental site is located at the Agricultural Experimental Station of the Technical University of Cartagena, south-eastern Spain (37°41′20″N, 0°57′03″W). This area is characterized by a Mediterranean semi-arid climate with warm, dry summers and mild winters. Average annual temperature is 17.5 °C, reaching maximum temperatures of 38 °C in summer and minimum temperatures of 0 °C in winter. Annual rainfall averages 320 mm, with high seasonal and inter-annual variability. Most precipitation occurs during the fall and winter months, but inter-annual droughts are also common. Average reference evapotranspiration, calculated by the Penman–Monteith method (Allen et al., 1998), is about 1250 mm $year^{-1}$.

Two RDCs were set up following the OPUR international standard procedure (Fig. 1). They consisted of 1 m^2 insulated flat pans tilted 30° to horizontal to ensure a good compromise between radiative energy loss and water recovery by gravity (Beysens et al., 2003). The water condensing on the surface at night was collected under gravity flow by a gutter and run to a container where it was stored and weighed. Both containers were provided with a siphon system for auto-emptying when full. One of the RDCs was dressed with the white standard foil (WSF), previously described, whereas the other was fitted with a 0.15 mm thick black low-density PE foil (in the following, BF), typically used as soil mulching in agriculture. This is a low-cost PE foil (0.8 \$ m^{-2}) which is made of 97.5% of low density PE, 2.5% of black of carbon and contains some antioxidant and thermal stabilizer additives.

Fig. 1. View of the two radiative dew condensers with the black PE foil (BF) and the white standard foil (WSF) fitted to the 30° tilted flat pans.

2.2. IR optical properties and emitted radiance of the foils

A spectrophotometer (FT-IR Bruker Vertex 70) was used for determining the spectral distribution (every 10 nm) of the absorptivity (=emissivity) and transmissivity of the foils for the mid IR spectrum (2.5–25 μm), under wet and dry conditions. Wet conditions were obtained by spraying water during five minutes on the foil samples. An average spectral curve, representing the mean of five repetitions, was calculated for each foil and surface status.

For a given wavelength λ, the emitted radiance (W, energy lost by radiation to the sky) was deduced from the Plank's law:

$$W = \frac{C_1}{\lambda^5} \frac{1}{\exp\left(\frac{C_2}{\lambda T_f}\right) - 1} \varepsilon \quad (1)$$

where $C_1 = 3.74 \times 10^8$ and $C_2 = 1.44 \times 10^4$ are constants, λ is the wavelength, ε is the measured emissivity of each foil configuration in each 10 nm wavelength interval and T_f (K) is the surface temperature. The calculations of W were performed with $T_f = 278$ K, which could be considered as a representative value of the foil temperature for dewy nights in the study area.

W and ε values were integrated over the following wavelength intervals: 2.5–7 μm, 7–14 μm and 14–25 μm. The range 7–14 μm was of special interest as it corresponds to the atmospheric window, the range considered in previous studies with the standard foil (e.g. Nilsson, 1994). The values of the emissivity weighed by the emitted radiance for both foils and under dry and wet conditions were calculated (Eq. (2)) for all spectrum ranges as:

$$\varepsilon^* = \frac{\sum \varepsilon_i W_i}{\sum W_i} \quad (2)$$

where ε_i and W_i are the emissivity and the emitted radiance, respectively, at wavelength λ_i.

2.3. Climate and dew measurements

During the observation period (May-2009 to May-2010) an automated meteorological station located at the vicinity of the RDCs provided the meteorological data required for the study. The following variables were continuously recorded at 2 m above ground: air temperature (T_a) and relative humidity (*RH*) (Vaisala HMP45C probe), wind speed (U_2) (Vector Instruments A100R anemometer) and downward atmospheric radiation (L_a) (Kipp & Zonen CGR 3 pyrgeometer). Rainfall (*P*) was measured by means of a tipping bucket gauge (Young 52203). Additional data of air temperature, relative humidity and wind speed were also collected close to the foils. Two infrared radiometers (Campbell Scientific SI – 111) located 30 cm over the foil supplied the foil surface temperature, T_f. Dew point (T_{dew}) was calculated from T_a and *RH*. The net radiation (R_n) during the night was calculated as $R_n = L_a - L_f$ with $L_f = \varepsilon^* \sigma T_f^4$, ε^* being the radiance weighed emissivity of the foil (see Section 3).

For each RDC, dew was collected at night from 20:00 to 8:00. The dew ran along an inclined gutter and passed through a plastic pipe into the container where dew was weighed by means of two high precision balances (COBOS, D-3000-CBJ; precision = 0.1 g). A wiper was used daily at dawn to scrape the extra water that remained on the foils. This quantity was added to the amount recovered in the collecting tanks to give the potential dew recovery. Previous analyses of dew collection on the foils indicated the scraped fraction represented about 15% and 20% of the total yield for the WSF and the BF respectively, a slightly lower value than the one reported by Muselli et al. (2002). In the following, the analysis concerns the potential dew recovery, which represents better the intensity of the condensation process. No damage due to scraping was noted on the foils during the measurements period. Eventually, dew yield was calculated as the difference between the maximum and the minimum weight of water recorded during the night.

Dew yield data were statistically analyzed by means of the statistical software package Statgraphics Plus (v.5.1), which performs analysis via a variance technique (ANOVA) to detect any significant differences between the dew yield of both WSF and BF. Tukey's range test at a 95% confidence level was calculated for comparison between dew yield data. Data from days corresponding to rainfall events at night were discarded from the data analysis because of the imprecision in measuring dew amount.

All sensors above described were scanned at 10-s interval and averaged hourly whereas the two precision balances were scanned at hourly interval. All data were recorded by a datalogger (CR1000 Campbell). The sensors and balances were periodically calibrated.

3. Results and discussion

3.1. Spectrometry and radiance analysis

Fig. 2 presents the spectral distribution of the foil emissivity in the range 2.5–25 μm for WSF (Fig. 2a) and BF (Fig. 2b), under dry and wet conditions. The curves were quite similar over the considered spectrum, with the exception of the region from 2.5 to 7 μm, where the emissivity of WSF was significantly lower than that of BF.

The emissivity under wet conditions was slightly higher than in dry conditions for both foils. The averaged emissivity of WSF increased 1.93% and 0.72% in the 2.5–25 μm range and the 7–14 μm range, respectively. The corresponding increases for BF were 0.26% and 0.60%. This result indicates that dew formation raised slightly the surface emissivity, the effect being more marked for WSF.

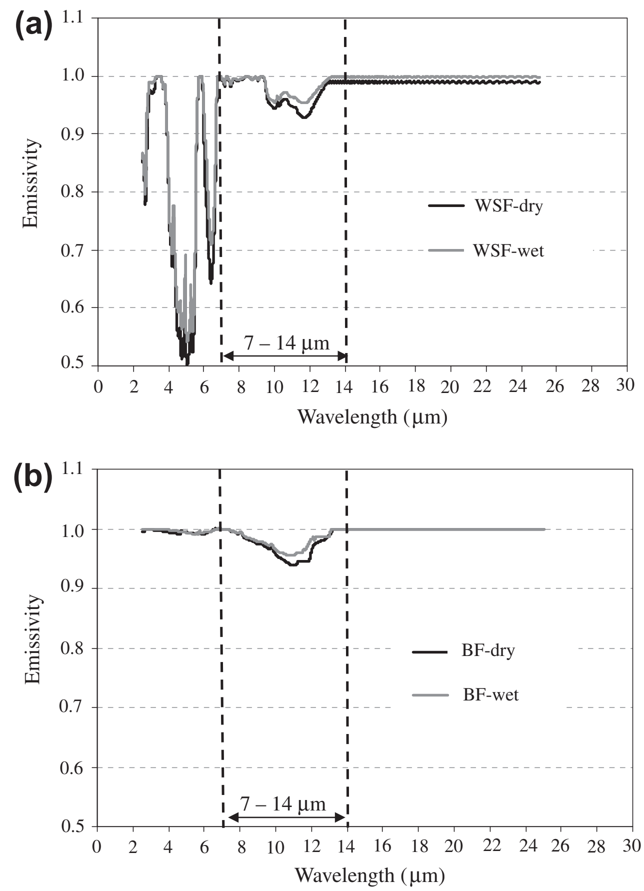

Fig. 2. Distribution of the foil emissivity (ε) for (a) WSF and (b) BF, under dry and wet conditions in the 2.5–25 μm range. Vertical bars delimit the 7–14 μm region (atmospheric window).

Whereas ε of both foils was found to be very similar in the range 7–14 μm, there were significant differences in the lower wavelength interval (2.5–7 μm) that affected to some extent the emitted radiance, *W* (Fig. 3a and b).

Integrating *W* over the three sub-ranges supplied useful information on the relative contribution of each sub-range to the total emitted radiance (W_{tot}) in the 2.5–25 μm range for the two foils under dry and wet conditions (Table 1). In all cases, the 7–14 μm region accounts approximately for 50% of W_{tot}, whereas the lower region and the upper region contributed to 7% and 43%, respectively. Under dry conditions, W_{tot} was higher for BF (267.3 W m^{-2}) than for WSF (262.0 W m^{-2}), that is a difference of 5.3 W m^{-2} which has to be ascribed mainly to the difference of *W* in the lower sub-range (19.4 vs 15.4 W m^{-2}). The trend was similar under wet conditions, but the differences were somewhat smaller: W_{tot} = 268.5 and 265 W m^{-2} for BF and WSF respectively, a difference of 3.5 W m^{-2} which was mainly due to the difference observed in the lower sub-range (19.4 vs 16.1 W m^{-2}), as for the dry foils. The presence of water on the foil surfaces slightly increased *W* in all sub-ranges, the increase being greater for WSF (+5 W m^{-2}) than for BF (+1.2 W m^{-2}).

Water also increased the values of ε^*, the emissivity weighed by the emitted radiance for both foils (Table 1). Among foils, the values of ε^* were very similar for the middle and upper sub-ranges, but presented differences in the lower sub-range. Under dry conditions, ε^* in the 2.5–7 μm interval was equal to 0.825 and 0.995 for WSF and BF respectively. Under wet conditions, the difference was somewhat smaller (0.850 and 0.996 respectively). Considering the whole spectrum range, BF presented the highest values of ε^* under dry (0.985 vs 0.971 for WSF) as well as wet (0.990 vs 0.980 for

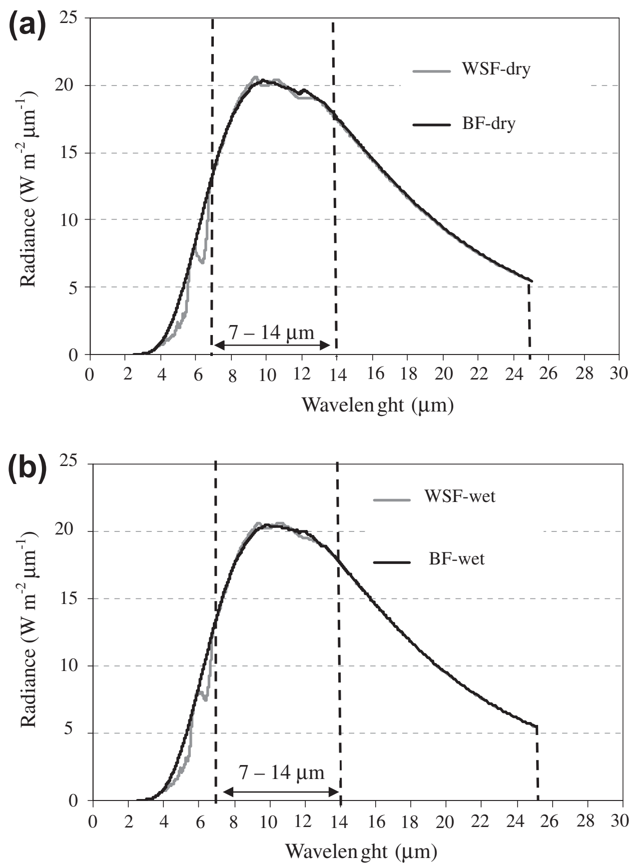

Fig. 3. Distribution of emitted radiance (W; W m^{-2}) in the 2.5–25 µm range according to the Planck's law assuming a surface temperature of 278 K for (a) WSF and (b) BF under dry and wet conditions. Vertical bars delimit the 7–14 µm region (atmospheric window).

WSF) conditions. Therefore, it could be recommended to use the radiance-weighed emissivity ε^* for the calculation and simulation of the emitted radiance from dew collecting surfaces.

Summarizing, both foils presented similar values of W, ε and ε^* for $\lambda > 7$ µm, but with significant differences in the range 2.5–7 µm. Accordingly, it can be concluded that BF presents a higher emissive power than WSF, due to the higher emissivity of BF in the range 2.5–7 µm, although the lower emissivity of the WSF in the lower spectral range allow to reflect sunlight and also acquire a role of passive air conditioning if it is applied on roofs. Besides, the higher reflectance of WSF in the short-wave (solar spectrum) provides lower surface temperature during the day than BF, resulting in WSF reaching more rapidly the dew-point temperature than BF (Sharan et al., 2007b).

3.2. Foils performance

During the 1-year experimental period, the number of dewy nights amounted to 175 and 163 for WSF and BF respectively (Table 2). Accounting for the lack of data due to sensor failure for 27 days of the observation period, the frequency of dew was 52% and 48% for WSF and BF respectively. Rainfall events (50 days) were unevenly distributed throughout the experimental period, amounting to a total of 490 mm.

Our results showed that dew yield was season-dependent. Three periods differing markedly in dew yield could be distinguished. The first one ranged from May-09 to July-09, the second one covered the summer months and the third corresponded to the period October-09 to May-10 (Table 2). The lowest monthly dew yield was observed in September, for both WSF (0.57 mm, 6 dewy nights) and BF (0.69 mm, 4 dewy nights), whereas the highest yield occurred in October (values of 3.18 mm and 3.83 mm for WSF and BF, respectively). The latter could be attributed to (i) strong radiative cooling at night due to the prevalence of clear sky conditions (only 2 rainfall events in October against 10 in September), (ii) high atmospheric humidity resulting from the high soil evaporation rate after heavy rainfalls (276 mm) on late September (Fig. 4) and (iii) low wind speed during the night. These conditions resulted in that the difference between dew-point and foil temperature reached its highest values in October.

Cumulated dew yield over the observation period was 17.36 and 20.76 mm for WSF and BF, respectively (Fig. 4). The results from the statistical analysis indicated that significant differences on dew yield were found between both foils, being the BF approximately 15% more efficient in recovering dew than WSF. The better performance of BF could be ascribed to its higher emissivity and emitted radiance (Table 1). This finding was confirmed with the nightly value of minimum foil temperature, which was on average 0.43 °C lower for BF than for WSF.

The dew yield histogram by classes of 0.05 mm (Fig. 5) suggested that the higher number of dewy events with low yield (less than 0.05 mm) for WSF were due to its hydrophilic surface properties. This characteristic allowed WSF to recover water from small events of dew (less than 0.10 mm) whereas the BF was less effective in this aspect. Conversely, BF was more efficient in the upper classes due to its higher emissivity. These respective advantages of WSF and BF appear to be of the same magnitude in the dew yield range 0.05–0.10 mm, where dew yield frequency for the two foils was identical (Fig. 5). These results make clear the influence of

Table 1
Integrated values of emitted radiance (W; W m^{-2}), emissivity (ε) and radiance-weighted emissivity (ε^*) in the 2.5–7 µm, 7–14 mm, 14–25 µm and the entire mid-infrared (MIR) ranges under dry and wet conditions.

Foil	Condition	Parameters	2.5–7 µm	7–14 µm	14–25 µm	Total MIR
WSF	Dry	ε	0.833	0.976	0.990	0.876
		ε^*	0.825	0.971	0.990	0.971
		W	15.4	131.3	115.3	262.0
	Wet	ε	0.854	0.983	0.998	0.893
		ε^*	0.850	0.980	0.998	0.980
		W	16.1.	132.6	116.3	265.0
BF	Dry	ε	0.996	0.976	0.998	0.992
		ε^*	0.995	0.972	0.998	0.985
		W	19.5	131.5	116.3	267.3
	Wet	ε	0.998	0.982	0.999	0.995
		ε^*	0.996	0.980	0.999	0.990
		W	19.5	132.5	116.5	268.5

Table 2
Number of dewy, rainfall and sensor failure nights and total monthly dew yield for the WSF and BF condensers during the observation period.

Year	Month	Number of days				Total dew yield (mm)	
		Dew on WSF	Dew on BF	Rainfall events	Sensor failure	WSF	BF
2009	May	22	22	3	0	2.47	2.43
	June	20	19	0	0	1.79	2.29
	July[a]	15	15	0	15	1.06	1.29
	August[a]	10	10	0	12	0.51	0.77
	September	6	4	10	0	0.57	0.69
	October	20	19	2	0	3.18	3.83
	November	17	15	2	0	1.84	1.99
	December	13	11	7	0	1.39	1.71
2010	January	13	11	7	0	1.12	1.53
	February	10	9	9	0	0.87	0.99
	March	15	15	7	0	1.30	1.62
	April	14	13	3	0	1.26	1.62
Annual		175	163	50	27	17.36	20.76

[a] Months affected by the sensor failure.

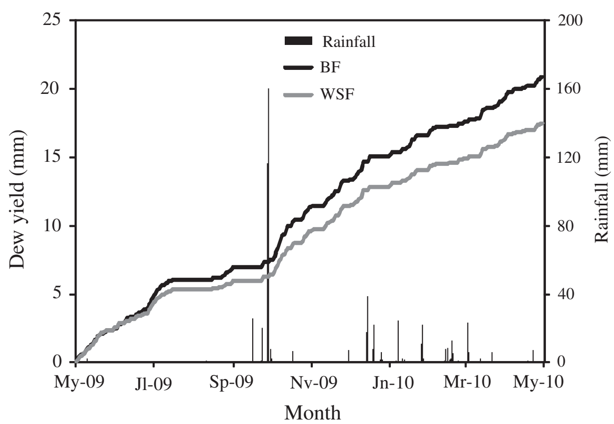

Fig. 4. Cumulated dew yield of WSF and BF condensers during the observation period. Bars represent rainfall events (mm).

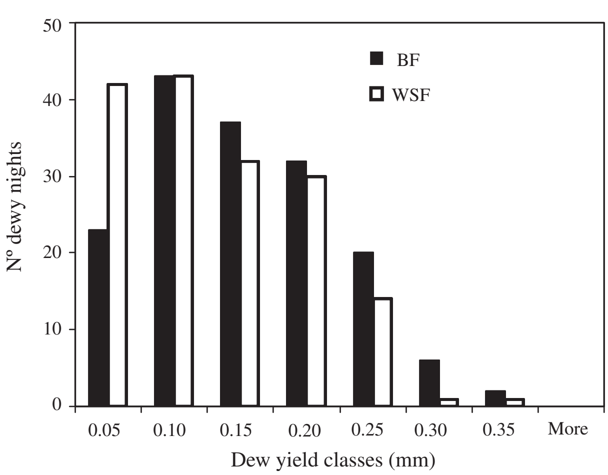

Fig. 5. Dew yield frequency histogram of WSF (white bars) and BF (black bars) during the observation period.

the dew yield potential in the experimental location on the comparison of yield performance between both foils, i.e. if the experiment had been carried out in another region characterized by smaller dew yield events (less than 0.10 mm), the hydrophilic properties of the WSF had probably allowed the WSF to collect more water than the BF. However, under the south-eastern Spain semi-arid conditions the BF has clearly better yield performance than the WSF.

In our study, the maximum dew yield recorded during a dewy night was 0.314 mm in December-09 for WSF and 0.316 mm in October-09 for BF. These values corresponded to the period from October-09 to December-09 when clear sky, low wind speed, and high values of atmospheric humidity were prevailing. Conversely, the lowest dew yield values for both foils were found during the driest months, i.e. July and August 2009 (Table 3). On annual scale, mean values were 0.105 mm d^{-1} and 0.128 mm d^{-1} for WSF and BF, respectively (Table 3).

3.3. Correlation with meteorological variables

The observed night dew yield, Y (mm $night^{-1}$), was first related to the dew point-to-air difference $\Delta T = T_{dew} - T_a$ (Fig. 6), that is, with the relative humidity, *RH*. The experimental data were fit to the following linear relationship to get an estimate of Y, Y_{est}, from the knowledge of ΔT.

$$Y_{est} = a_1(\Delta T - a_2) \quad (3)$$

where a_1 (in mm °C^{-1}) is the dew yield sensitivity to ΔT and a_2 the threshold value of ΔT below which condensation was not observed (Note that the threshold value of RH would be ~75%, Fig. 6). There were no significant differences in the parameter values between the two foils ($a_1 = 0.049 \pm 0.0056$ mm °C^{-1} and $a_2 = -4.2$ °C ± 0.26 for WSF, $a_1 = 0.051 \pm 0.0059$ mm °C^{-1} and $a_2 = -4.6$ °C ± 0.29 for BF). The dew yield sensitivity was in between the values found by Muselli et al. (2006b) and Muselli et al. (2009). Overall, the predictive performance of Eq. (3), characterized by standard statistical parameters (see Table 4) could not be considered as satisfactory. The experimental data presented considerable scatter over the whole range of ΔT, indicating that ΔT alone was a poor descriptor of dew yield.

To refine the correlation analysis, the residuals of Eq. (3) ($r = Y - Y_{est}$) were calculated and related to other climatic variables, revealing that the residuals were mainly dependent on the nightly net radiation, for both WSF and BF (Fig. 7).

Subsequently, Eq. (3) was multiplied by a function of R_n, $g(R_n)$, to account for this dependence. After testing various types of function, a decreasing hyperbolic function was found to supply the best fit (lowest root mean square error between observed and estimated values). The proposed empirical model to predict Y from T_a, T_{dew} and R_n was:

$$Y_{est} = f(\Delta T)g(R_n) = (b_1(\Delta T + b_2))\left(1 + \frac{b_3}{R_n}\right) \quad (4)$$

Table 3
Monthly and annual maximum, average, and standard deviation of dew yield for the WSF and BF condensers during the observation period.

Month		Dew on WSF			Dew on BF		
		Maximum	Average	Std. Dev.	Maximum	Average	Std. Dev.
2009	May	0.210	0.112	0.060	0.201	0.110	0.051
	June	0.226	0.094	0.070	0.246	0.120	0.062
	July	0.163	0.070	0.042	0.155	0.086	0.049
	August	0.119	0.050	0.031	0.141	0.077	0.028
	September	0.161	0.143	0.020	0.198	0.174	0.022
	October	0.237	0.167	0.051	0.316	0.201	0.061
	November	0.274	0.123	0.081	0.270	0.133	0.079
	December	0.314	0.127	0.089	0.307	0.155	0.091
2010	January	0.172	0.107	0.051	0.238	0.139	0.070
	February	0.213	0.096	0.070	0.215	0.111	0.058
	March	0.205	0.086	0.066	0.231	0.108	0.069
	April	0.233	0.092	0.059	0.250	0.124	0.072
Annual		0.314	0.105	0.031	0.316	0.128	0.035

Std. Dev.: Standard deviation.

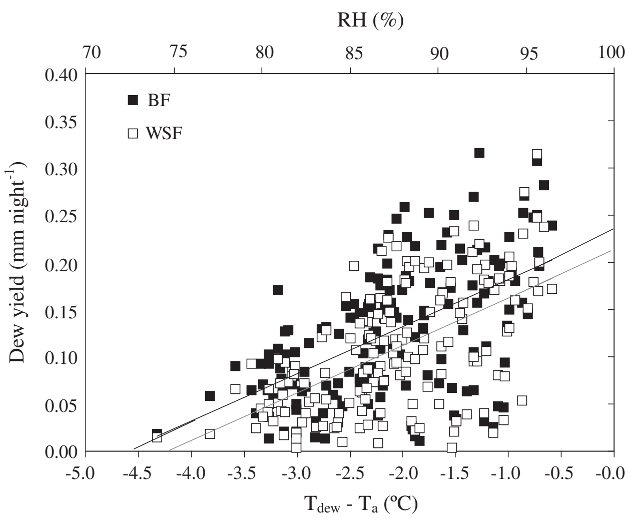

Fig. 6. Correlation of dew yield Y (mm night^{-1}) with $\Delta T = T_{dew} - T_a$ (°C, lower scale) and relative humidity RH (%, upper scale) for WSF (white symbols) and BF (black symbols).

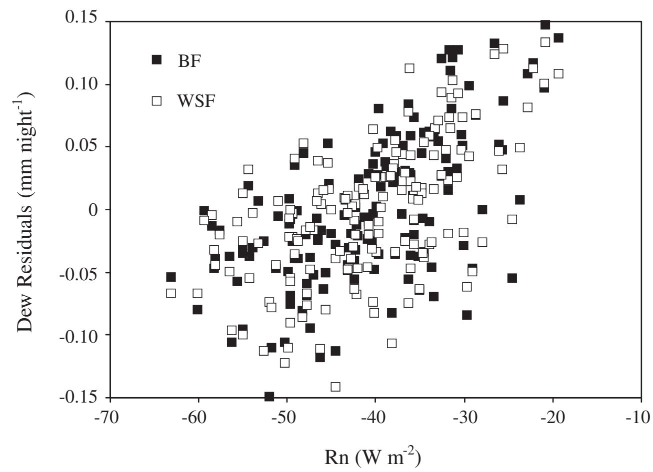

Fig. 7. Relationship between the residuals (r) of Eq. (3) and the mean nightly net radiation (R_n) for WSF (white symbols) and BF (black symbols).

Table 4
Values of (i) fitted parameters and (ii) statistical parameters characterizing the predictive performance for Eqs. (3) and (4).

	WSF	BF
(i) Eq. (3): $Y_{est} = a_1((T_d - T_a)+a_2)$		
a_1 (mm night^{-1} °C^{-1})	0.049 ± 0.005	0.051 ± 0.006
a_2 (C^{-1})	−4.2 ± 0.260	−4.6 ± 0.297
R^2	0.33	0.32
RMSE (mm night^{-1})	0.043	0.045
MBE (mm night^{-1})	0.003	0.003
(ii) Eq. (4): $Y_{est} = b_1((T_d - T_a) + b_2)(1 + b_3/R_n)$		
b_1 (mm night^{-1} °C^{-1})	0.126 ± 0.011	0.129 ± 0.011
b_2 (C^{-1})	3.9 ± 0.128	4.1 ± 0.137
b_3 (W m^{-2})	19.21 ± 0.94	18.93 ± 0.88
R^2	0.63	0.65
RMSE (mm night^{-1})	0.035	0.035
MBE (mm night^{-1})	0.002	0.002

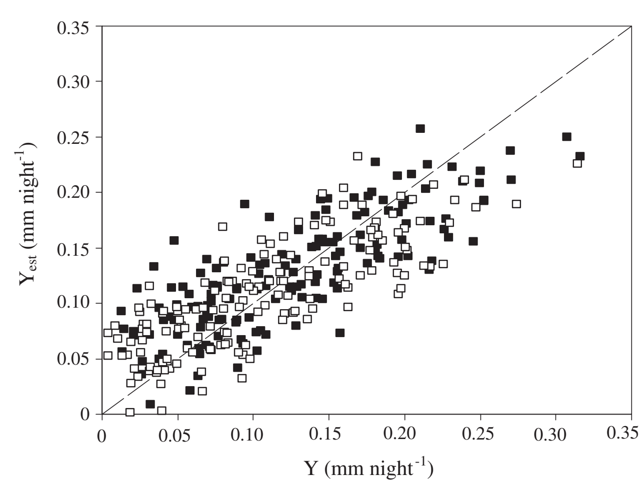

Fig. 8. Comparison between observed (Y) and estimated (Y_{est}) night dew yield, using Eq. (4) (WSF: white symbols, BF: black symbols). The dashed line is the 1:1 relationship.

with $b_1 = 0.126$ and 0.129, $b_2 = 3.9$ and 4.1 and $b_3 = 19.21$ and 18.93 W m^{-2} respectively for WSF and BF. The addition of R_n as supplementary predictive variable improved considerably the predictive performance with respect to Eq. (3) (Fig. 8; Table 4).

Using wind speed at 2 m (U_2) as additional variable to ΔT and R_n improved only marginally the predictive performance (results not shown). The distribution of dew yield vs wind speed (Fig. 9)

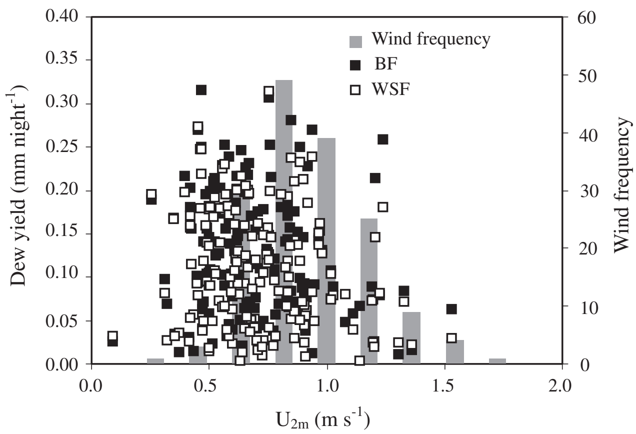

Fig. 9. Correlation of dew yield with wind speed U_{2m} and wind speed frequency classes for WSF (white symbols) and BF (black symbols). Wind frequency has been only plotted for the range where dew formation occurs (0–2 m s^{-1}).

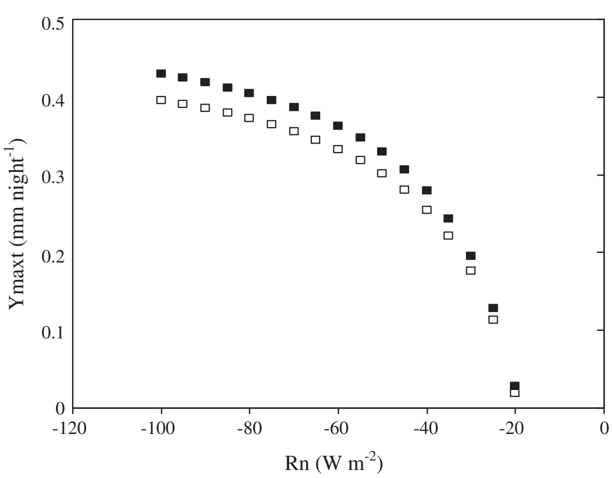

Fig. 10. Maximum dew yield as a function of foil net radiation as predicted from Eq. (5) for WSF (white symbols) and BF (black symbols).

indicated that most of the events of dew occurred when U_2 was lower than 1 m s^{-1}.

3.4. Potential dew yield

If $T_{dew} = T_a$, Eq. (4) theoretically provides the maximum attainable yield Y_{max} under our study conditions (Fig. 10):

$$Y_{max} = 0.49\left(1 + \frac{19.21}{Rn}\right) \quad \text{and} \quad Y_{max} = 0.53\left(1 + \frac{18.93}{Rn}\right) \tag{5}$$

respectively for WSF and BF. As it could be deduced from the values of b_3 (19.21 for WSF and 18.83 for BF), no condensation would occur for nightly mean values of R_n higher than -20 W m^{-2}. The curves indicated a fast increase in dew recovery potential in the range -20 to -40 W m^{-2}. For $R_n = -100$ W m^{-2}, value that could be considered as the maximum radiative cooling power for a condenser (Monteith, 1957; Sharan et al., 2007c), the maximum potential yield would be 0.40 and 0.43 mm $night^{-1}$ for WSF and BF respectively, confirming the slightly higher potential for dew recovery observed with BF.

4. Conclusion

RDCs have been demonstrated to serve as a complementary source of drinking water, mainly in developing countries, rural areas or small islands, where free-access to water and energy is expensive. In these regions they are ahead of other techniques such as distillation or desalination, or deep underground water extraction, all of which require a large amount of energy and a massive infrastructure to operate.

Our study under south-eastern Spain semi-arid conditions demonstrated that the potential for dew yield of a low-cost black PE foil (BF) was slightly higher than that of the OPUR-standard foil (WSF), although the BF does not present the hydrophilic properties of the latter. This disadvantage of BF resulted in less dewy days observed, but was more than compensated on the quantitative aspect – i.e. the amount of annual recollected water – by the higher emissivity and radiative cooling power of BF in the lower range (2.5–7 μm) of the mid IR spectrum. It should be pointed out that the hydrophilic properties of WSF might predominate over the higher emissive power of BF in regions characterized by small dew yield events.

Our results suggested that (i) the knowledge of the emissivity in the whole IR spectrum is necessary to correctly assess the performance of the foil and (ii) ensuring a high emissivity over the whole IR spectrum appeared more effective for increasing RDC yield than improving surface hydrophilic properties. On a practical point of view, BF could be considered as a suitable material for large-scale RDCs, as in our study, it presented several advantages over the standard reference foil, i.e. higher dew collection performance, longer lifespan and much lower cost. Dealing with the last two aspects, it must be pointed out that if the WSF were manufactured in large quantities and anti-UV treated, its cost might be reduced and its lifespan extended.

With respect to yield performances, we showed that RDCs installed in semi-arid coastal sites similar to our study site (Southern Spain) could recollect approximately 20 mm per year. This value was somewhat higher than those observed in previous studies in other Mediterranean coastal zones situated more at North, such as Corsica or the Croatian Coast (Muselli et al., 2002, 2009; Beysens et al., 2007), but lower than those reported for arid countries such as the Negev, Israel (Kidron, 1999). It should be stressed that the highest values of daily dew yield were observed mainly during periods following heavy rainfalls, due to high soil evaporation and high nocturnal atmospheric humidity. Therefore, it is likely that the amount of recollected dew would depend in part on the importance, frequency and time occurrence of rainfall events that affect the humidity content of the air at the vicinity of the condenser. This was confirmed by our correlation analysis between nightly yield and atmospheric variables, where the predominant predictive variables were found to be the relative humidity and the net radiation of the foil.

An empirical relationship between yield and the two mentioned predictive variables was proposed that explained about two-thirds of the total variance, and could be used to estimate daily dew yield with reasonable accuracy. From this relationship, it was derived that the potential yield could be, expressed as a function of R_n and could reach up to a maximum of 0.40 mm $night^{-1}$ under strong radiative cooling ($R_n \sim -100$ W m^{-2}).

Finally, it has to be stressed that the foil net radiation is required to predict dew yield with a reasonable accuracy, implying that the temperature of the foil surface should be either measured or estimated by means of a model describing the energy balance of the surface (Finch and Gash, 2002). Such a model would be of paramount interest (i) for assessing the performances of RDCs in different locations and climates and (ii) in the design of optimal RDC structure, shape and orientation.

Acknowledgments

The authors acknowledge the Foundation Seneca (Murcia, Spain) and the Ministry of Science and Innovation for the financial support of this study through the grants 02978/PI/05 and AGL2010-15001 respectively.

References

Agam, N., Berliner, P.R., 2006. Dew formation and water vapor adsorption in semi-arid environments – a review. J. Arid Environ. 65, 572–590.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. Irrigation and Drainage Paper 56. FAO, Rome, 300 pp.

Beysens, D., 1995. The formation of dew. Atmos. Res. 39, 215–237.

Beysens, D., Milimouk, I., Nikolayev, V., Muselli, M., Marcillat, J., 2003. Using radiative cooling to condense atmospheric vapor: a study to improve water yield. J. Hydrol. 276, 1–11.

Beysens, D., Muselli, M., Nikolayev, V., Narhe, R., Milimouk, I., 2005. Measurement and modelling of dew in island, coastal and alpine areas. Atmos. Res. 73, 1–22.

Beysens, D., Clus, O., Mileta, M., Milimoukc, I., Musell, M., Nikolayev, V.S., 2007. Collecting dew as a water source on small islands: the dew equipment for water project in Bisĕvo (Croatia). Energy 32, 1032–1037.

Finch, J.W., Gash, J., 2002. Application of a simple finite difference model for estimating evaporation from open reservoir. J. Hydrol. 255, 253–259.

Jacobs, F.G.A., Heusinkveld, B.G., Berkowicz, S.M., 2002. A simple model for potential dewfall in an arid region. Atmos. Res. 64, 285–295.

Jacobs, F.G.A., Heusinkveld, B.G., Berkowicz, S.M., 2008. Passive dew collection in a grassland area, The Netherlands. Atmos. Res. 87, 377–385.

Kidron, G.J., 1999. Altitude dependent dew and fog in the Negev Desert, Israel. Agric. For. Meteorol. 96, 1–8.

Kidron, G.J., 2000. Analysis of dew precipitation in three habitats within a small arid drainage basin, Negev Highlands, Israel. Atmos. Res. 55, 257–270.

Kidron, G.J., Herrnstadt, I., Barzilay, E., 2002. The role of dew as a moisture source for sand microbiotic crusts in the Negev Desert, Israel. J. Arid Environ. 52, 517–533.

Lekouch, I., Muselli, M., Kabbachi, B., Ouazzani, J., Melnytchouk-Milimouk, I., Beysens, D., 2011. Dew, fog, and rain as supplementary sources of water in south-western Morocco. Energy 36, 2257–2265.

Monteith, J.L., 1957. Dew. Quart. J. Royal Meteor. Soc. 83, 322–341.

Moro, M.J., Were, A., Villagarcıa, L., Canton, Y., Domingo, F., 2007. Dew measurement by Eddy covariance and wetness sensor in a semiarid ecosystem of SE Spain. J. Hydrol. 335, 295–302.

Muselli, M., Beysens, D., Marcillat, J., Milimouk, I., Nilsson, T., Louche, A., 2002. Dew water collector for potable water in Ajaccio (Corsica island, France). Atmos. Res. 64, 297–312.

Muselli, M., Beysens, D., Soyeux, E., 2006a. Chemical composition of dew water from passive radiative condenser in Corsica Island (France). J. Environ. Qual. 35, 1812–1817.

Muselli, M., Beysens, D., Milimouk, I., 2006b. A comparative study of two large radiative dew water condensers. J. Arid Environ. 64, 54–76.

Muselli, M., Beysens, D., Mileta, M., Milimouk, I., 2009. Dew and rain water collection in the Dalmatian Coast, Croatia. Atmos. Res. 92, 455–463.

Nilsson, T.M.J., 1994. Optical scattering properties of pigmented foils for radiative cooling and water condensation: theory and experiment. Ph.D. Thesis, Department of Physics, University of Technology, Göteborg, Sweden.

Richards, K., 2009. Adaptation of a leaf wetness model to estimate dewfall amount on a roof surface. Agric. For. Meteorol. 149, 1377–1383.

Sharan, G., 2007a. Harvesting dew to supplement drinking water supply in arid coastal villages of Gujarat. Indian Institute of Management. W.P. No. 08-05.

Sharan, G., Singh S, Clus, O., Milimouk-Melnytchouk, I., Muselli, M., Beysens, D., 2007b. Roofs as Dew Collectors: III. Special Polyethylene Foil on a School in Sayara (NW India). In: Proceedings of the 4th Conference on Fog, Fog Collection and Dew (La Serena, Chile), pp. 251–254.

Sharan, G., Beysens, D., Milimouk-Melnytchouk, I., 2007c. A study of dew water yields on Galvanized iron roofs in Kothara (North-West India). J. Arid Environ. 69, 259–269.

Steinberger, Y., Loboda, I., Garner, W., 1989. The influence of autumn dewfall on spatial and temporal distribution of nematodes in the desert ecosystem. J. Arid Environ. 16, 177–183.

Vermeulen, A.T., Wyers, G.P., Romer, F.G., Van Leeuwen, N.F.M., Draaijers, G.P.J., Erisman, J.W., 1997. Fog deposition on a coniferous forest in the Netherlands. Atmos. Environ. 31, 375–386.