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Analysis of different condensing surfaces for dew harvesting

Larissa Corraide da Silva[a,*], Delly Oliveira Filho[a], Hewlley Maria Acioli Imbuzeiro[a]
and Paulo Marcos Barros Monteiro[b]

[a] Federal University of Vicosa, Brazil
[b] Federal University of Ouro Preto, Brazil
*Corresponding author. E-mail: larissa.corraide@ufv.br

LC, 0000-0003-3280-1198

ABSTRACT

Due to water shortages in several places in the world, alternative water sources such as atmospheric water and greywater have been studied. Dew water harvesting by passive radiative cooling is an unconventional water source that is easy to use, install, and shows great potential in several places in the world. This paper aims to experimentally evaluate the dew yield through passive radiative cooling in Vicosa city, Minas Gerais, Brazil by using standard white plastic for dew harvesting, developed by the International Organization for Dew Utilization (OPUR), polypropylene plastic, black plastic, packaging tape, and anodized aluminum as condensing surfaces during two different periods. The polypropylene plastic and packing tape materials used in this present research have not been researched before in the literature. However, they have demonstrated potential for harvesting dew. As a result, the average water collected was, respectively, 0.151, 0.135, 0.140, 0.127, and 0.046 mm/night using the OPUR standard plastic, polypropylene plastic, black plastic, and packaging tape, and anodized aluminum as condensing surfaces. Although relatively small water volumes were harvested, this water should not be neglected since it can supplement the water demand for irrigation, human and animal consumption, among other uses in drought periods.

Key words: dew yield, drought, radiative cooling, water sources

HIGHLIGHTS

- Water vapor can be harvested to supplement traditional water sources using low-cost materials.
- We analyzed two low-cost materials that have not been studied for dew harvesting yet.
- There is no statistically significant difference between the amount harvested by each low-cost material and the amount harvested by the OPUR standard plastic.

1. INTRODUCTION

Water vapor is abundant in the atmospheric air, and it can be harvested as an alternative to supplement the traditional water sources. Water scarcity is growing globally, and there are isolated communities that lack access to such an essential good (Ernesto & Jasson 2016). In response to this water shortage, alternative water sources such as desalination, greywater reuse, and atmospheric water harvesting (rain, fog, and dew) have been studied, developed, and implemented as alternative water sources in several regions of the world. Dew harvesting in Chile, rainwater in Australia, United Kingdom, and the United States, and greywater reuse in Australia, Japan, and Spain are some examples (Ángel *et al.* 2016; Carvajal *et al.* 2018). Although the amount of dew harvested is small compared to the amount of rainwater, it should not be neglected since, in drought periods, it may be substantial for irrigation and or human consumption, especially as a potable water source, for example. Meunier & Beysens (2016) affirm in their study that dew, drizzle, and fog, in addition to the rainwater, can expressively raise the amount of atmospheric water collected to around 40% ± 20%.

Dew is a global event in which atmospheric vapor condenses on a surface. It is an unconventional water source that can complement water resources and represent a substantial amount of water in water scarcity places (Mileta *et al.* 2006; Tomaszkiewicz *et al.* 2015, 2017). Dew water harvesting by using passive radiative cooling provides excellent benefits over its simplicity of use and installation. In the last decades, studies have been conducted to maximize the amount of

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water collected by using passive radiative cooling with hydrophilic materials, which favors the condensation of water vapor (Sharan *et al.* 2017). Additionally, it is a technology that does not use active energy, and it can be used in different regions of the planet (Beysens *et al.* 2006; Sharan 2011; Khalil *et al.* 2015; Ernesto & Jasson 2016; Jarimi *et al.* 2020).

In this process, the condensing surface loses heat to the environment, causing its temperature to be lower than the surrounding atmospheric air. This cooling process usually happens on cold nights, with high humidity, wind with speeds below 4.4 m/s, and clear sky (Beysens 2016). Thus, when finding a surface with a temperature at or below the dew point temperature, water vapor condenses. After condensation, water droplets slide by gravity and can then be stored (Tomaszkiewicz *et al.* 2015).

For this process to occur efficiently, the condensing surface should have a high emissivity and low thermal mass (Tomaszkiewicz *et al.* 2015; Carvajal *et al.* 2018). Also, surface wettability is an essential factor in the nucleation, growth, and coalescence process of water droplets. Thus, it interferes with the amount of dew harvested (Gerasopoulos *et al.* 2018).

Several studies using different types of dew collectors through passive radiative cooling have been analyzed worldwide, such as experiments in France (Grenoble), Tanzania (Dodoma), Croatia (Zadar), and Sweden (Ernesto & Jasson 2016). Most of these systems consist of a flexible material installed on an inclined surface to collect water directed to a collector by gravity (Khalil *et al.* 2015; Gerasopoulos *et al.* 2018). Generally, a small-scale prototype with the same size of condensing surface, for example, 1 m^2, and different materials are used to compare dew yields in the different regions. A few experiments are performed on a large scale, such as condensing surfaces integrated into building roofs (Sharan 2011; Carvajal *et al.* 2018).

This paper aims to compare the amount of dew harvested through passive radiative cooling in Vicosa city, Minas Gerais, Brazil, using different condensing surfaces. They are: (i) the standard plastic for dew harvesting developed by the International Organization for Dew Utilization (OPUR) (OPUR – ORGANIZATION FOR DEW UTILIZATION 2018); (ii) black plastic commonly used in construction and plantations; (iii) anodize aluminum; (iv) polypropylene plastic (cellophane); and (v) polypropylene packaging tape. Furthermore, this paper validates, for Vicosa city, the dew yield estimation model through passive radiative cooling developed by Beysens (2016).

2. METHODOLOGY

The experimental work was performed in the Energy Lab of the Agricultural Engineering Department of the Federal University of Vicosa, 20° 77′ South latitude, 42° 87′ West longitude, and 665 m altitude, during the period from August 21st to September 21st, 2018 (winter) and from September 22nd to October 23rd, 2018 (spring). According to the Koppen classification, Vicosa's climate is Cwb type, which means a mesothermal climate with hot and rainy summers, and cold and dry winters (Freitas *et al.* 2017).

2.1. Dew harvesting condensers

Passive condensers of 0.25 m^2 (0.5 m × 0.5 m) were installed 1 m above the ground. The structure inclination angle was 30°, which favors dew formation and radiative cooling. This angle was defined as the optimal angle, according to the study performed by Beysens *et al.* (2003).

We constructed two structures for each condensing surface material, except for polypropylene plastic (cellophane) and polypropylene packaging tape, where only one structure for each was made because of material limitation (Figure 1).

2.1.1. Condensing surfaces

The OPUR white plastic is considered a standard plastic, made of low-density polyethylene with 5% of the volume of TiO_2 microspheres – titanium dioxide (0.19 μm diameter) and 2% of $BaSO_4$ microspheres – barium hydroxide (0.8 μm diameter), 0.83 emissivity, and 0.3 mm thickness. This plastic has hydrophilic properties that favor nucleation, besides high near-infrared emissivity (7–14 μm) (Maestre-Valero *et al.* 2011; Sharan 2011). Despite the favorable characteristics for dew harvesting, this plastic, explicitly developed for this purpose, is expensive because it is manufactured at a small scale (FOB price of US$10/$m^2$). Thus, one of the alternatives analyzed in some studies is a low-cost recycled black plastic (Maestre-Valero *et al.* 2011) (US$0.21/$m^2$) commonly used in agriculture and construction. According to Maestre-Valero *et al.* (2011), this type of material is composed of 97.5% low-density polyethylene and 2.5% carbon and thermal stabilizers and antioxidant additives. Black plastic has a high emissivity that can reach 95% (Almeida *et al.* 2012). The use of metals has also been studied as a condensing surface. Sharan (2011) studied galvanized sheet metal used in roof construction and commercial aluminum sheet for water vapor condensation in India. This present research also studied 0.5 mm thick anodized aluminum, developed for the

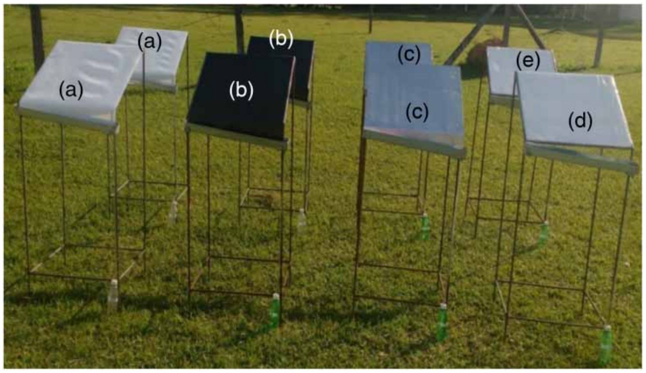

Figure 1 | Dew condensers installed at the experiment site (a): OPUR standard plastic, (b): black plastic (c): anodized aluminum, (d): polypropylene plastic (cellophane) and (e): polypropylene packaging tape.

production of high-performance radiation reflectors and manufactured by Lucchi. This material has an emissivity of about 0.82 (Liu 2006; Çengel & Ghajar 2012; Sant'anna 2015; Lucchi 2018).

We observed water condensation on polypropylene tape in preliminary experiments. Thus, we sought materials that had similar characteristics, and the thin cellophane polypropylene plastic, commercially known as only cellophane paper, was chosen, besides the packing tape. There is, up to this time, no scientific research in the consulted literature that was performed using these two materials for passive dew harvesting.

The condensing surfaces were thermally insulated with a 20 mm thick expanded polystyrene sheet, commonly known as Styrofoam, and they were set up in the northeast direction, where night winds prevail.

Condensed water vapor during the night period was collected by gravity and scraping. At the bottom end of each structure, a gutter directed the water through a hose to the water storage container. Figure 2 shows the collection system used in the experiment.

The dew yield was collected daily at sunrise. The volume was measured, both the amount collected in the water container and the amount obtained by manually scraping the condensing surface using a 100 mL graduated beaker. Manual surface scraping using a squeegee was performed with the surface size being only 50 by 50 cm; probably on larger surfaces, scraping is neither recommended nor feasible.

During these experiments, hourly ambient air temperature, dew point temperature, relative air humidity, and wind speed were obtained from the automatic weather station, managed by the National Institute of Meteorology and located 1.5 km away from the experiment site (INMET – National Institute of Meteorology 2018). It is a limitation of the study since data were not collected at the experiment site.

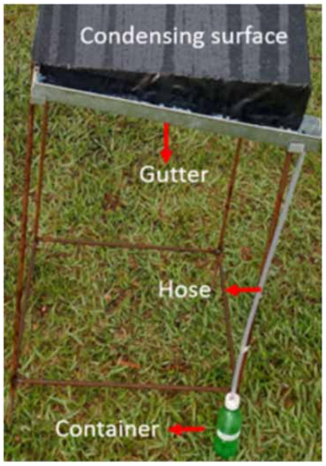

Figure 2 | Dew harvesting system used in the experiment.

2.2. Statistical analysis of results

Statistical analysis of the results was performed by comparing the groups (bilateral t-test) to compare the amount of dew collected using the standard white plastic (OPUR) with the dew yield by using the other materials studied (black plastic, anodized aluminum, polypropylene plastic (cellophane) and polypropylene packaging tape). The samples were considered to be a normal distribution, and the significance level chosen was 95%.

2.3. Model validation

Beysens (2016) developed a model using a unit emissivity condensing surface where only data from at least 1 h before sunrise is needed to estimate dew yield over the entire night period, as shown in Equation (1). Thus, only site altitude, ambient air temperature, dew point temperature, wind speed, and cloudiness data are required.

$$D_y = \begin{cases} \{0.37[1 + 0{,}204323\,H - 0{,}0238893\,H^2 - (18{,}0123 - 1{,}04963\,H \\ +0{,}21891\,H^2)10^{-3}\,T_d]\left(\frac{T_d + 273{,}15}{285}\right)^4 \times \left(1 - \frac{N}{8}\right)\Big\} & \text{if Positive} \\ +[0{,}06\,(T_d - T_a)]\left(1 + 100\left\{1 - e^{\left(-\left(\frac{S}{S_0}\right)^{20}\right)}\right\}\right) & \\ 0 & \text{if negative} \end{cases} \tag{1}$$

where,
D_y = Dew yield during the night, considering 12 h (mm/night);
H = Site elevation (km);
T_d = Dew point temperature (°C);
T_a = Ambient air temperature (°C);
N = Cloud cover (oktas);
S = Wind speed (m/s) at 10 m elevation; and
S_o = Wind speed of 4.4 m/s (maximum speed for dew formation (Beysens 2016).

However, in this present research, dew yield was hourly estimated for the whole night period. Subsequently, the dew yield for that night was considered to be the average hourly dew yield estimated to increase accuracy. Using this methodology to estimate dew yield, the duration in hours of the night period should be considered (Equation (2)) since Equation (1) assumes a night time of 12 h. Thus, this estimate should be corrected using Equation (3) (Beysens 2016).

$$\tau = \frac{24}{128}\cos^{-1}\left[\tan\alpha\,\tan\left(-23.5\,\cos\left(\frac{360\,(d - 355)}{364}\right)\right)\right] \tag{2}$$

where,
τ = Night length (hours);
α = Location latitude; and
d = Day of the year.

$$D_{yT} = \frac{T}{B} D_Y \tag{3}$$

where,
D_y = Dew yield, considering a nocturnal period of 12 h (mm/night);
B = Full analysis period of 12 h/night;
T = Period of analysis (h/night); and
D_{yT} = Dew yield, considering a nocturnal period of T hours (mm/night).

The air temperature, dew point temperature, and wind speed data used to estimate dew yield were obtained from INMET (Brazilian National Institute of Meteorology). However, sky cloud data during the night period are no longer analyzed and computed for Vicosa city since the conventional weather station, which had operators to make this visual cloud estimate, is no longer in operation. Thus, we used weather forecast data hourly from intellicast.com for the experiment's night time (Intellicast 2018).

Intellicast provides specific weather information for 60,000 sites in the United States of America and around the world. Also, it has a technically advanced forecasting system and provides accurate forecasting (Janeiro *et al.* 2015; Intellicast 2018; Lu *et al.* 2018).

Therefore, it was possible to validate and adjust the dew yield estimation model for the studied region (Vicosa, MG) by following the same methodology adopted by Beysens (2016) to validate the model for 10 different places. However, emissivity was assumed near to one in the model. The Beysens model was validated by evaluating the correlation between the accumulated values estimated by the model and the accumulated values experimentally collected from the first to the last day of the experiment for each condensing surface under analysis (Equation (4)). The sum of the values was adopted to smooth out the daily uncertainties. A linear adjustment was made to determine the proportionality factor α between the estimated dew yield and the amount collected experimentally (Beysens 2016).

$$\sum_{d_f}^{d_1} D_{ye} = \alpha \sum_{d_f}^{d_1} D_{yc} \tag{4}$$

where,

d_f = First experiment day;
d_1 = Last experiment day;
d_{ye} = Estimated dew yield (mm/day);
d_{yc} = Dew yield collected experimentally (mm/day); and
α = Proportionality factor.

3. RESULTS AND DISCUSSION

3.1. Weather variables

The average nighttime meteorological variables: ambient air temperature, relative air humidity, dew point temperature, wind speed, and cloudiness were computed for both experiment periods (Table 1).

We can highlight that the first period of analysis corresponds to the end of the dry season, with less precipitation and less cloudiness. The second one corresponds to the beginning of the rainy season with more cloudiness.

It can be observed that the average values of air relative humidity and wind speed did not vary significantly during the two experimental periods**.** However, the average air temperature and, consequently, the average dew point temperature were higher for the second experimental period (spring). Moreover, the cloudiness index was also higher during the experimental phase in spring, which may negatively contribute to dew yield through passive radiative cooling.

Table 1 shows that winter has more favorable dew harvesting conditions due to the smaller difference between the average ambient air temperature and average dew temperature because of the lower dew point temperature. Also, winter is the driest time of the year for Vicosa, which requires a higher water demand and, consequently, dew may be more relevant to supplement the water demand.

Table 1 | Average nighttime meteorological variables for Vicosa city during the experiment periods

Experiment periods	Average ambient air temperature (°C)	Average Relative Humidity (%)	Average dew temperature (°C)	Average wind speed (at a 10 m of height) (m/s)	Average cloudiness (oktas)
1st period (winter period) August 21st to September 21st, 2018	14.87	91.80	13.49	0.31	3
2nd period (spring period) September 22nd to October 23rd, 2018	18.40	91.21	16.89	0.35	5

3.2. Number of days with dew for each condensing surface

The experiment to harvest dew by passive radiative cooling was carried out over 64 days: 32 days during winter and the other 32 days during the spring season. Table 2 summarizes the number of days that dew was observed for each substrate.

In winter, there were only four days without dew on all condensing surfaces tested. It rained in the other six days, which can be considered atypical for this time of year. Therefore, it is noted that dew formation could be observed for anodized aluminum in approximately 43.75% of nights and 68.75% for other condensing surfaces. In spring, there was no dew on 10 nights on all condensing surfaces. Also, it rained only one day during the night. Therefore, dew formation was observed in approximately 34.39% of the spring nights studied for anodized aluminum condensing surfaces and 66.50% for other condensing surfaces.

The percentage of nights with dew was approximately the same, both for the winter and spring experiments, for all studied condensing surfaces, except for anodized aluminum. Maestre-Valero *et al.* (2011) observed a percentage of days with dew of about 48% in Spain (Cartagena) during one year (from May 2009 to May 2010). Muselli *et al.* (2009) obtained a percentage of about 39.7% in Zadar, Croatia, from July 2003 to October 2006. Both used in their studies the standard plastic (white plastic) developed by OPUR.

3.3. Comparing daily dew yield

The average daily dew yield during the experiment was 0.177, 0.153, 0.060, 0.163, and 0.161 mm/night for the winter experiment and 0.125, 0.100, 0.032, 0.116, and 0.109 mm/nigh for the spring experiment by using standard OPUR standard plastic, black plastic, and anodized aluminum polypropylene packaging tape, and polypropylene plastic (cellophane) as condensing surface, respectively. Considering the two experimental periods under analysis, the average water collected by using the OPUR standard plastic was 0.151, 0.127 by using the black plastic, 0.046 by using anodized aluminum, 0.140 by using packaging tape, and 0.135 mm/night by using polypropylene plastic (cellophane) as condensing surfaces. Figure 3 shows the total amount of dew harvested by each condensing surface collected during the winter and spring experiment.

We can note that the OPUR standard plastic, black plastic, packing tape, and polypropylene plastic (cellophane) harvested similar yields. Comparing to the OPUR standard plastic amount, black plastic harvested during winter and spring experiments, respectively, about 86.3% and 80.2%; packing tape harvested approximately 92.0% and 92.4% during winter and spring, respectively; polypropylene plastic harvested 90.6% and 87.6%, respectively for winter and spring periods. However, anodized aluminum showed the worst proportion of dew harvested of about 33.6% and 25.2% for winter and spring, respectively, due to its low emissivity.

We can observe that the total amount of dew harvested in spring was less than the volume harvested during winter, when dew was observed for more days on the condensing surfaces. The cloudiness index may explain this difference since average relative humidity was close for the two experiment periods. This index showed distinct monthly variation, high in spring and lower in winter. This variable negatively influences the surface cooling during the night and, consequently, the dew formation since clouds have a warming effect. During a cloudy sky, less energy is lost by the surface to the atmosphere since less shortwave radiation reaches the atmosphere. On the other hand, more energy is lost by the surface to the atmosphere in a clear sky due to the increase in longwave loss, decreasing air temperature.

The difference in the quantities collected using different condensing surfaces may be explained by the condensing surface materials' different properties, such as the emissivity, hydrophilic characteristics, and roughnesses that interfere with the

Table 2 | Number of days that dew was observed for each substrate during the winter and spring experiment period

	Number of days with dew	
Substrate	**Winter**	**Spring**
OPUR standard plastic	22	21
Black plastic	22	21
Anodized aluminum	14	11
Packing tape	22	21
Polypropylene plastic	22	21

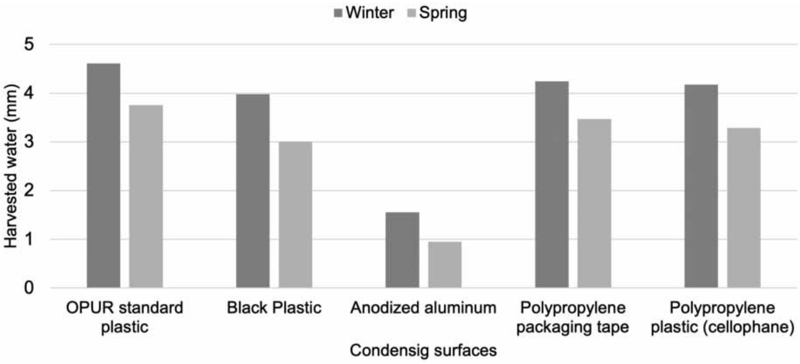

Figure 3 | Dew harvested during the winter period (August 21st, 2018 to September 21st, 2018) and winter period (September 22nd, 2018 to October 23rd, 2018) studied for the condensing surfaces analyzed in Vicosa, MG.

droplet slip. According to Tomaszkiewicz *et al.* (2015), although galvanized metal condensing surfaces are more durable, they require particular painting to maximize radiative cooling and hydrophilic properties. This type of material also produced smaller amounts of dew (Sharan 2011) due to smaller emissivity. In our experiment, anodized aluminum collected around 30.46% of the OPUR standard plastic amount harvested.

Contrary to this present study, Maestre-Valero *et al.* (2011) obtained a more considerable amount of dew using black plastic (20.76 mm/year) than by using OPUR standard plastic (17.36 mm/year) in a study conducted in Cartagena, Spain. According to the authors, this fact can be attributed to the higher emissivity of black plastic.

However, in this present research, OPUR standard plastic showed better results than black plastic. It is believed that the better performance of plastic developed by OPUR can be attributed to its hydrophilic properties, which facilitate droplet nucleation and the sliding of drops (Maestre-Valero *et al.* 2011; Sharan 2011).

The results of OPUR standard plastic and black plastic, OPUR standard plastic and packing tape, and OPUR standard plastic and polypropylene plastic (cellophane) were not significantly different, as *p*-values were greater than 0.05 and $T_{calculated} < T_{critical}$, which means that these materials essentially harvest the same amount of dew. On the other hand, the results obtained with OPUR standard plastic and anodized aluminum were significantly different (*p*-value$>$ 0.05 and $T_{calculated} < T_{critical}$).

3.4. Economic comparison among condensing surfaces

When comparing the price of the OPUR standard plastic (USD 10.00/m²) with the other materials' price, we can note that it does not always justify its use since they were not statistically significantly different (*p*-value >0.05).

The black plastic price per square meter (USD 0.23/ m^2) represents about 2.3% of OPUR standard plastic price. The price of the packing tape (USD 0.70/m^2) represents about 6.94% of the price of the OPUR standard plastic. Finally, the price of polypropylene plastic (cellophane) (USD 0.33/m^2) represents about 3.32% of the standard plastic price.

On the other hand, the price of the anodized aluminum (per square meter) is USD 24.25, which represents more than double the price of the OPUR standard plastic. In addition, it collects a litter amount of dew compared to the other condensing surfaces.

However, studies about the degradation of all materials used are also needed to plan the maintenance costs appropriately.

3.5. Dew yield model validation

Comparing the estimated accumulated values and the experimentally measured accumulated values of dew yield, it is observed that the black plastic and polypropylene plastic presented the best adjustment coefficient for the experimentally measured value, about 1.13 and 1.18, respectively (Figure 4(a) and 4(b)). Using both OPUR standard plastic and packing tape, the estimated dew yield obtained an adjustment coefficient of 1.35 and 1.22, respectively (Figure 4(c) and 4(d)). On the other hand, the estimated dew yield using anodized aluminum was underestimated by about 42%, as shown in Figure 4(e).

Beysens (2016) experimentally determined that the adjustment coefficient for the 10 sites analyzed in his study would be an average value of about 0.95 considering a surface with an emissivity of one.

The difference between estimated and measured values may also be justified by the fact that the meteorological parameters used in the model were obtained from the weather station located about 1.5 km away from the experiment site. Also, the

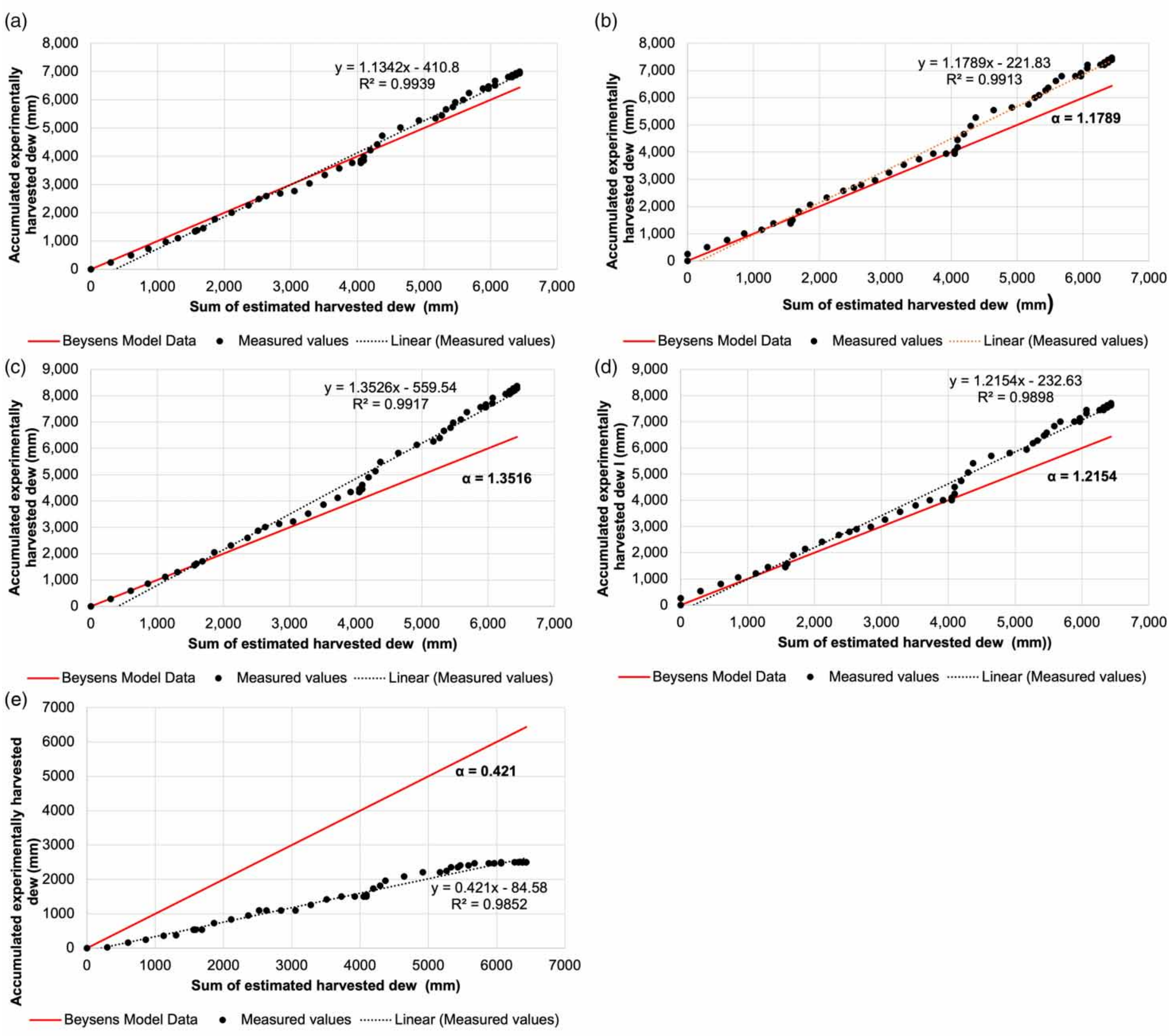

Figure 4 | Relationship between estimated cumulative values and experimentally measured cumulative values for 64 days of dew harvesting for: (a) black plastic; (b) polypropylene plastic, (c) OPUR standard plastic; (d) packing tape and (e) anodized aluminum.

difference in altitude between the weather station and the experiment site is about 32 m. According to (Kidron 1999) and (Beysens 2016), this difference may be caused by the difference in altitude between the experiment's place and where meteorological data was collected. Besides, the cloudiness indexes used in the model were obtained from weather forecasts, which, although current, may cause uncertainty in the estimate. Also, the experiments' location is located about 100 m from a lake, which may contribute to higher air humidity due to air advection.

Despite the difference found due to different materials emissivity, it is concluded that the model developed by Beysens (2016) can be used to estimate dew yield in the studied area. The obtained adjustment coefficient can be used so that more accurate values can be estimated.

4. CONCLUSIONS

This research experimentally compared the amount of dew harvested over two-periods (winter and spring) using the OPUR standard plastic, black plastic, anodized aluminum, and polypropylene plastic (cellophane), and polypropylene packaging tape as condensing materials. Although the OPUR standard plastic has a higher amount of dew harvested, around

0.151 mm/night, it has a high cost because it is still produced on a small scale. Materials such as polypropylene packaging tape and polypropylene plastic (cellophane) harvested a similar amount of dew, about 0.140 mm/night and 0.135 mm/night, respectively, and at a much lower cost than OPUR standard plastic. Also, there is no statistically significant difference between the amount harvested by using the standard OPUR standard plastic and the amount of dew collected by using black plastic, polypropylene packaging tape, and polypropylene plastic (cellophane).

Although polypropylene packaging tape, and polypropylene plastic (cellophane) have not been studied in the literature up to this date, they showed potential for harvesting dew.

The condensing sheets' durability and the collected water quality were not studied in this experiment. Nevertheless, it was observed that the condensing surfaces remained without any sign of degradation during the experiment days. Further studies about different condensing surface degradation are advisable to have a more accurate analysis among the condensing surfaces.

During the experimental period of dew harvesting, small amounts of water were collected. However, this water may be indispensable to supplement the water demand for irrigation, human and animal consumption, among other uses.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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