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Comparing plastic foils for dew collection: Preparatory laboratory-scale method and field experiment in Kenya

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Abstract

Passive dew collection could be a viable option as a source of irrigation water in arid areas. The plastic foil acting as a condensing surface plays a key role in the passive dew collection regime. A laboratory method for comparing various plastic foils for dew collection was prepared and tested. The focus was on creating a method for measuring the attributes affecting dew condensation and the flow of dew droplets on the measured surface. A low-density polyethylene foil designed for dew collection, white polyethylene plastic, black polyethylene plastic, and white polyvinyl chloride plastic were used as the test plastics. The laboratory dew yields were compared with model calculations. In addition, field trials were conducted in arid conditions in Maktau, Kenya, to compare with the laboratory measurement. Results from the hardware model tests were not reflected in the results obtained from the field conditions. The laboratory tests showed that the dew-harvesting quality of plastic foils is difficult to evaluate using the laboratory test rig. A more comprehensive evaluation regime requires tests performed in field conditions or further development of the test rig used here.

Keywords: dew harvesting, plastic foil, drought,

Nomenclature

C_c – Specific heat capacity of the condensing surface

C_w – Specific heat capacity of water

c_c – Water concentration on the surface

c_a – Water concentration in air outside the laminar layer

D – Diffusion coefficient

k – Mass transfer coefficient

L_c – Length of the condensing surface

L_w – Latent heat of vaporization or condensation

m_c – Mass of the condensing surface

m_w – Mass of water

Nu – Nusselt’s number

P_{cond} – Conductive heat exchange energy

P_{conv} – Convective heat exchange energy

P_{lat} – Latent condensation energy

P_{rad} – Heat radiation energy

Re – Reynold’s number

S_c – Condensing surface area

Sh – Sherwood’s number

T_c –Temperature of the condensing surface

T_d – Dew point temperature

v – Fluid velocity

x_c – Absolute humidity on the condensing surface

x_a – Absolute air humidity

p_{sat} – Saturated vapor pressure

p_c – Vapor pressure at the condensing surface

δ – Thickness of the boundary layer

ρ_a – Air density

ν – Kinematic viscosity of the fluid

θ – Inclination angle of the condensing surface

1. Introduction

In most climate zones, the annual dew quantity available is small compared with the precipitation quantity (Vuollekoski et al., 2015). However, dew quantity in certain areas of arid zones can exceed the amount of rainfall, and can even be the main source of liquid water for plants (Agam & Berliner, 2006). Based on long-term observations in the Negev desert, Israel, dew occurred 176 times per year and was equivalent to an annual average 33 mm of precipitation (Berkowicz et al., 2004). Hill et al. (2015) reported that approximately half of the water intake of certain plants in the Negev desert originates from dew. In such areas, passive dew collection could be a viable option as a source of irrigation water. Dew condensation, utilising passive radiative cooling on a given surface, is dependent on the cooling power caused by infrared irradiation towards the night-time sky, through the Earth's atmosphere's highly transparent window in the wavelength range 8e13 mm. According to the Stefan-Boltzmann law, this irradiation is limited to roughly 100 W m^{-2} for clear nocturnal skies (Eriksson & Granqvist, 1982). This limits the theoretical maximum of the dew condensing rate on exposed objects to around 0.1 l m^{-2} h^{-1}, resulting in 0.8 l m^{-2} or mm per night depending on the number of condensing hours (Jones, 2014; Monteith, 1957; Revankar, 2009). In field trials, the maximum dew quantity collected by passive dew collectors has been reported to be ca. 0.6 mm per night (Berkowicz et al., 2004). However, reported quantities for dew yields usually settle in the range of 0.1 – 0.3 mm per night (Berkowicz, 2009; Beysens et al., 2003; Jacobs, et al., 2008; Khalil et al., 2014; Maestre-Valero et al., 2011; Muselli et al., 2002; Nilsson et al., 1994; Sharan, 2011). Planar collectors constructed of a plastic foil (typically around 1 x 1 m^2) mounted on a rigid polystyrene sheet (25 mm thick) are the most commonly used passive dew collectors in research applications (Berkowicz et al., 2004; Clus et al., 2008; Gandhidasan & Abualhamayel, 2005; Jacobs et al., 2008; Lekouch et al., 2011; Maestre-Valero et al., 2011; Muselli et al., 2009; Nilsson, 1996; OPUR, 2020). The polystyrene sheet prevents thermal radiation from the soil and surrounding objects from increasing the temperature of the dew collection foil and is usually supported by a metallic frame. The condensing surface is most commonly tilted around 30° from the horizontal (Berkowicz et al., 2004; Clus et al., 2008; Gandhidasan & Abualhamayel, 2005; Jacobs et al., 2008; Lekouch et al., 2011; Maestre-Valero et al., 2011; Muselli et al., 2009; Nilsson, 1996; OPUR, 2020). The plastic foil plays a key role in the passive dew collection regime. The International Organization for Dew Utilization (OPUR) recommends using a low-density polyethylene foil

(LDPE), originally developed and presented by Nilsson et al. (1994), as a standard for dew recovery or collection comparisons. Usually this LDPE is referred to as OPUR foil. It has high emissivity in the infrared (IR) region (emissivity of thermal energy), especially in the 8 – 13 mm range due to the added fillers: 2% barium sulphate (BaSO4, diameter 0.8 mm) and 5% titanium dioxide (TiO2, diameter 0.19 mm) (Nilsson et al., 1994). This contributes to radiative cooling of the foil. Further, the mineral fillers in OPUR foil affect the wetting properties of the foil, making it more hydrophilic (Maestre-Valero et al., 2011; Nilsson et al., 1994). High reflectance of OPUR foil in the visible light region reduces foil heating by daylight in the early morning and late evening hours, thus prolonging the effective time of dew formation on the foil (Maestre-Valero et al., 2011; Nilsson et al., 1994). OPUR foil has been used in many of reported dew collection experiments (Beysens et al., 2003, 2006; Clus et al., 2008; Gandhidasan & Abualhamayel, 2005; Jacobs et al., 2008; Lekouch et al., 2011; Maestre-Valero et al., 2011; Muselli et al., 2002, 2009; Nilsson, 1996; Nilsson et al., 1994; Sharan, 2011; Vargas et al., 1998). Many commercially available plastic foils, such as polyethylene plastic (PE), polyvinylchloride plastic (PVC) etc., could also be considered suitable for dew collection. Although the field trials reflect the reality of dew collection, they are laborious from the viewpoint of dew collection material development. Also, the natural variation of ambient conditions in field conditions, makes the evaluation of the foil material properties difficult. Therefore, an evaluation regime for various dew-collecting surfaces would greatly benefit from a simple and reliable test method used for comparing dew-collecting attributes under controlled and reproducible ambient conditions. The laboratory tests can be conducted regardless of the time of day and the condensation rate is adjustable. Research would also benefit from an evaluation method for enhancing the dew collection properties of the condensing surface foil materials. However, in practise, the use of the described planar dew collectors requires field trials due to the difficulties in artificially creating in the laboratory a radiative cooling effect that is similar to the night-time sky conditions. In this study, this question is addressed by preparing and testing a laboratory method for comparing the dew collection efficiency of various plastic foils. Previous dew-related studies have implemented hardware models (Richards, 2002a, 2002b; Richards & Oke, 2002; Spronken-Smith & Oke, 1999). However, these studies focussed on modelling entire physical urban and/or rural landscapes in miniature, rather than focussing on the dew-collecting attributes of a surface material (Beysens, 2016) used a laboratory setup with a Peltier-element to determine parameters that affect dew condensation for theoretical modelling purpose. The focus of the study was on the parameters and not on material comparison. There are, as far as we know, no applicable laboratory methods for simulating the radiative cooling of materials under a night sky. Our focus was on creating a method for measuring the attributes affecting the condensing and flowing of the dew droplets on the measured surface in a controlled laboratory environment. The aim of the measurements was to compare the dew-collecting ability of various plastic foil types. To verify our results, we compared them with dew yields collected during a field trial carried out under arid conditions in southern Kenya and with the results of theoretically calculated dew outputs.

2. Materials and methods

2.1 Laboratory experiments

To create a dew-condensing surface, the surface has to be cooled below the dew point temperature of the ambient air. The cooling of the condensing surfaces of the laboratory hardware model was carried out by thermal conductance through the measured plastic foils by implementing 40 x 40 x 4.8 mm 53 W Peltier elements. The hot side of the Peltier element was glued with thermally conductive silicone glue to a 50 x 50 x 16-mm heat sink, which was cooled by a fan (12 VDC 0.15 A, diameter 45 mm). The tested plastic foils were glued onto the cold side of the Peltier elements. Polyvinyl acetate adhesive was used for the purpose (Fig. 1).

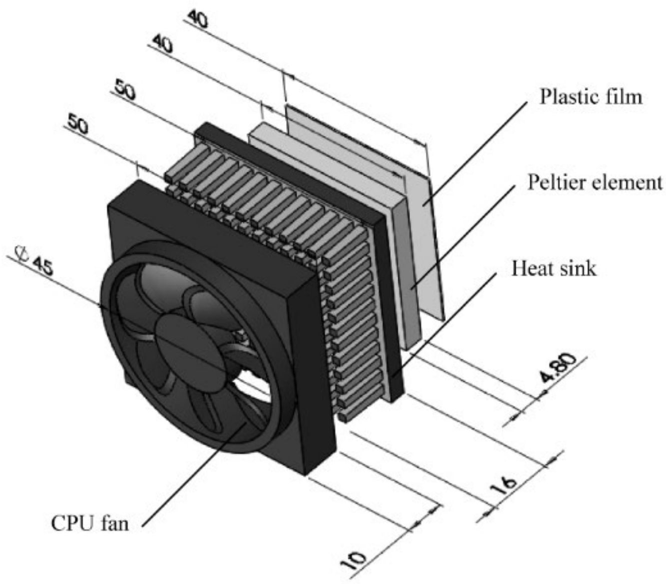

Figure 1. A sketch of the implementation of the cooling surface to test the plastic foil properties. Dimensions are in mm.

Two Peltier elements (Fig. 1) were wired in parallel with each other (Fig. 2) and the whole circuit was fed with electrical power from an adjustable power source. The voltage and current were measured for each element, and were 6.0 VDC and 6.0 A between the positive (+) and ground (-) poles, respectively. This corresponds to 36 W. A measurement set-up, referred to as "wind tunnel", was constructed within the climate chamber. The use of two condensing elements was justified by the need to perform two simultaneous measurements with the plastic foil samples.

The measurement set-up (Fig. 2) consisted of a rectangular insulated hardboard box with two fans (12 VDC, 0.19 A, diameter 80 mm) installed at both ends of the box, so that an air flow similar to a wind tunnel was created. One fan provided suction, whilst the other blew air into the box. The cooling surfaces (Fig. 2) were attached to the rear face of the hardboard box perpendicular to horizontal and along the wind direction. When collecting droplets with gravity-induced flow, gravity acts on the condensed droplets as sin θ (Beysens et al., 2003), and thus inclination angle of the condensing surface $\theta = 90°$ so as to introduce the greatest possible gravitational force on the droplets.

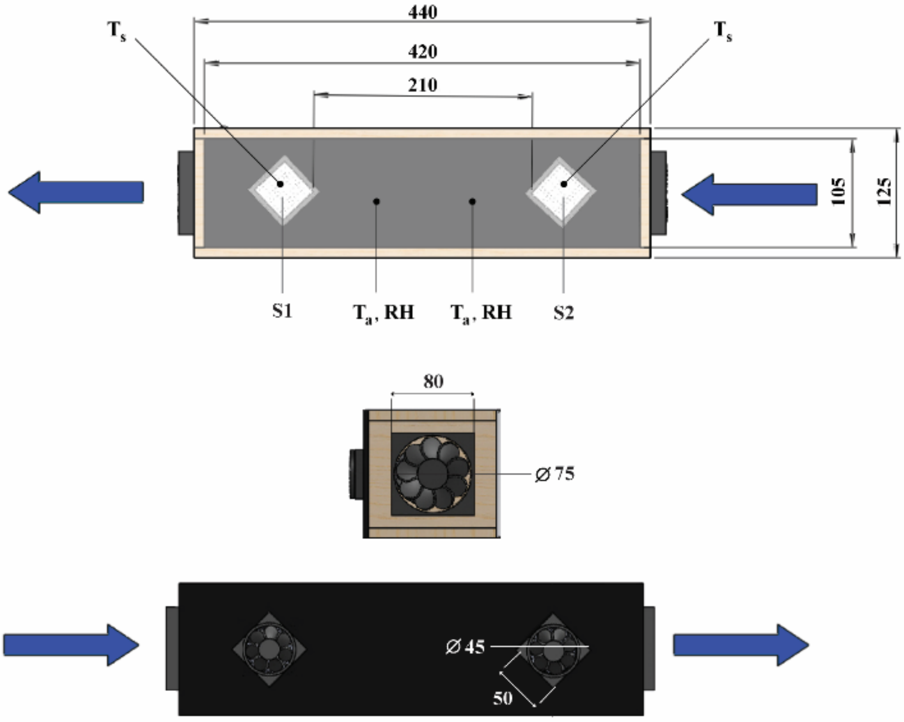

Figure 2. A sketch of the wind tunnel set-up used for dew collection measurements (measures are given in mm) from front (top figure), side (middle figure) and backside (bottom figure). Two Peltier elements, functioning as condensing surfaces (S1 and S2), were mounted on heat sinks, which were cooled with 45-mm diameter fans. T_s and T_a indicate surface and ambient temperature sensors, respectively and *RH* indicate relative humidity sensors. Blue arrows indicate the direction of the airflow created with two 75-mm diameter fans.

A climate chamber (WEISS WKL100, PIDSO Vienna, Austria) was used to provide controlled ambient conditions for the hardware model. The conditions in the climate chamber were set to 20.0 °C (temporal temperature variation ±0.3 – ±1.0 °C at a point and spatial temperature variation within the chamber ±0.5 – ±2.0 °C given by manufacturer) and a relative humidity of 70% (temporal variation given by manufacturer ±1 – 3%) with the corresponding dew point 14.4 °C. These conditions were chosen as they were assumed to represent the field conditions at the field experiment site in Kenya. The climate chamber also worked reliably within this operational range.

Surface airflows were measured with a wind probe (FVAD1, Ahlborn, Ilmenau, Germany) horizontally, vertically, and orthogonally in relation to the dew-condensing surface (Table 1). The highest airflows for S1 and S2 were measured in the horizontal direction in relation to the condensing element. The airflow at the surface affects the dew-condensing rate (Beysens, 1995; Monteith, 1957), as it affects the thickness of the boundary layer and brings humid air to the condensing surface. The airflow measurements were repeated three times for each surface material. These airflows were used in the modelling of dew condensation.

Table 1. Airflows (m s^{-1}) measured continuously at the condensing surfaces (S1 and S2) during an ongoing measurement process.

	S1	S2
Horizontal	1.70	2.15
Vertical	0.70	0.60
Orthogonal	0.63	0.60

Dew condensed on the surfaces was collected into vessels placed under the elements. The surfaces were neither wiped nor shaken during or after the experiment. The collected water mass was thus a result of gravity-induced flow accumulation. The collected water was measured gravimetrically with a balance (Mettler-Toledo, Columbus, OH, USA) with readability of 0.1 mg and reproducibility (standard deviation) of 0.1 mg. The containers, with previously determined masses, were weighed together with the collected dew immediately following each experiment.

During the experiments, the surface temperature of the condensing surface was measured by attaching K-type thermocouples (standard limit tolerance of 1.1 °C or ±0.4%) on the surface of the plastic using aluminium tape. The ambient air conditions were monitored during the experiments with K-type thermocouples and air relative humidity sensors (HIH-4000, Honeywell International Inc., Morris Plains, NJ, USA) that were mounted near the cooling surfaces (Fig. 2). Measurement data were stored on a PC using a data acquisition system (34970A Data Acquisition, Agilent technologies, Inc. Santa Clara, CA, USA). Measurement data were scanned and stored at a 10-s interval. The measurement time for the dew collection was set to four hours. The measurement time was chosen, so that it is possible to do undertake several tests during a single day but still long enough to measure dew quantities, between which differences can be observed.

2.2 Tested plastic foils

Four different types of plastic foils were assessed in the experiments (Table 2): two polyethylene (PE) and one polyvinylchloride (PVC) plastic foil, and an OPUR foil. Values for contact angles between the surface and water were measured with a goniometer (SMART e CAM 200, KU Leuven, Leuven, Belgium), with an accuracy of 0.1° given for contact angles between 5° and 180° and with an image area of 5.7 – 5.4 mm^2.

Various contact angle values were measured at different locations on the OPUR foil samples (Table 2). The large difference in the measured contact angles is likely to originate from a heterogeneous distribution of the surface additives $BaSO_4$ and TiO_2. Emissivity of the plastic surfaces were measured with FT-IR spectrometer (Perkin-Elmer Spectrum One, Waltham, MA, USA). The obtained spectral curve was a mean of five repetitions. We paid a special attention on the spectral range of 7 – 14 mm, which is the atmospheric window over which the average emissivity was calculated (Table 2).

Table 2. Measured thickness, contact angle with water and emissivity in the infra-red region for the plastic foils that were tested in this article. The thickness was measured with a micro meter screw gauge, the contact angles between the surface and water were measured with a goniometer, the emissivity of the plastic surfaces were measured with an FT-IR spectrometer.

Material	Thickness (µm)	Contact angle with water (°)	Emissivity (7 - 14 µm)
PEW	50	95.1	0.975
PEB	50	95.1	0.927
OPUR	340	51.9–80.5*	0.967
PVC	370	89.5	0.965

*Various contact angles were measured at different measurement points for OPUR plastic.
PEW= White PE plastic foil, PEB = White PE plastic foil, PVC = White PVC plastic foil.

2.3 Field measurements in Maktau, Kenya

The dew collectors were installed at Maktau, Kenya (3° 25’33 S, 38° 8’22 E, 1060 m above sea level) to conduct dew-collecting experiments in an arid climate zone between March 1 and March 31, 2016. The studied site experiences rainy seasons from early November to end of December - “short rains”, and from March to June - “long rains”, whilst the hot and dry season occurs in January and February, and dry and cool season between June and October (Appendix Table A). Thus, our measurement period was at the beginning of the “long rains”. The dew collected at that time could be particularly beneficial to agronomy during this period of the year since this period covers the planting time of most common annual field crops cultivated in the region. Dew could be collected and used as reserve irrigation water to help the plants to survive over their vulnerable early development phases when i.e. during dry spells that occur within the rainy season. The collectors were placed on a western edge of a cropland of an area of 1 ha approximately 4 m from bushland in the west, and2e6 m from the Maktau weather station. The cropland expanding 100 m east from the collectors grows maize and beans and the farmhouses are located 40 m from the collectors (Fig. 3).

The dew collectors consisted of a 25-mm thick polystyrene sheet supported by a stainless-steel frame. The plastic foil, onto which the dew condensed, was mounted on the polystyrene sheet. The plastic foil sheet, i.e. the condensing surface, had an area of 1 x 1 m^2. Surface angles were approximately 30° in relation to the horizontal, which is considered optimal for dew harvesting. At this angle, a gain in cooling in the order of 20% was observed with respect to a horizontal reference condenser. Furthermore, at this angle, gravitational force acting on the drops is still 50% of the maximum available force obtainable when perpendicular (Beysens et al., 2003). The ten collectors all faced west, prolonging the dew-condensing time in the morning before sunrise from the east. The dew collectors were placed in a random order side by side or diagonally in relation to each other (Fig. 3). The distance between the sides were of minimum 100 mm. Dew condensed on the surface during the night flowed into a gutter due to gravity, and further on through a small tube into a bottle or vessel placed on the ground at the end of the gutter (Fig. 4). The plastic foils used on the condensing surfaces in the field conditions were the same as those tested in the laboratory (Table 2).

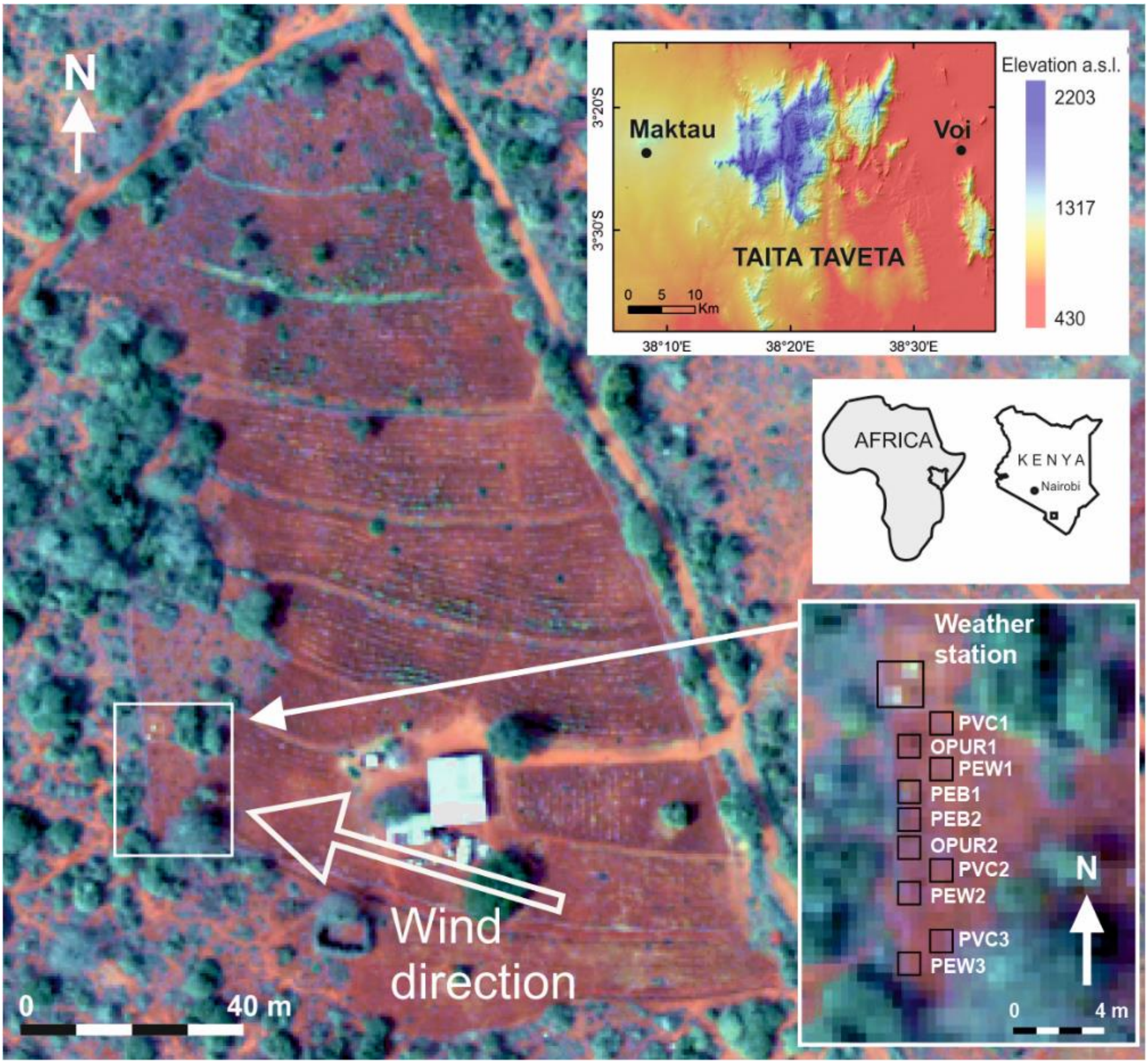

Figure 3. The experimental site in Maktau, Kenya. Aerial photograph Leica RCD 30, 0.5 m spatial resolution, January 21, 2014. Elevation model adopted from Abera et al. (2020).

The weather station at the experimental field site had been running since August 2014, and was the only automatic weather station operating near the study area. It was setup by CHIESA project (Climate change impacts on ecosystem services and food security in Eastern Africa) and was managed by Taita Research Station of the University of Helsinki. The weather station data were stored on a data logger (CR1000, Campbell Scientific, Logan, UT, USA). Data were acquired once per minute and stored as 30-min means. The sensors connected to the data logger measured air temperature and air relative humidity (CS215, Campbell Sci.) at a one-metre height above ground level. Precipitation was measured with a rain gauge (ARG100, Campbell Sci.) placed 1.5 m above the ground. Wind speed and direction were measured using a wind monitor (WMS 05103, Campbell Sci.) placed 2 m above the ground. Net solar radiation was recorded using a pyranometer (CS300, Campbell Sci.).

The temperatures of the condensing plastic surfaces were measured with T-type thermocouples (standard limit tolerance of 1 °C or ± 0.75%) mounted on the surface of the dew collectors with a piece of tape. The ambient relative humidity was measured with sensors (HIH-4000, Honeywell Int.) mounted on the back of the rack of the dew collectors. The data were stored on a data logger (CR1000, Campbell Sci). Measurement data were acquired once per minute and stored as a 10-min average.

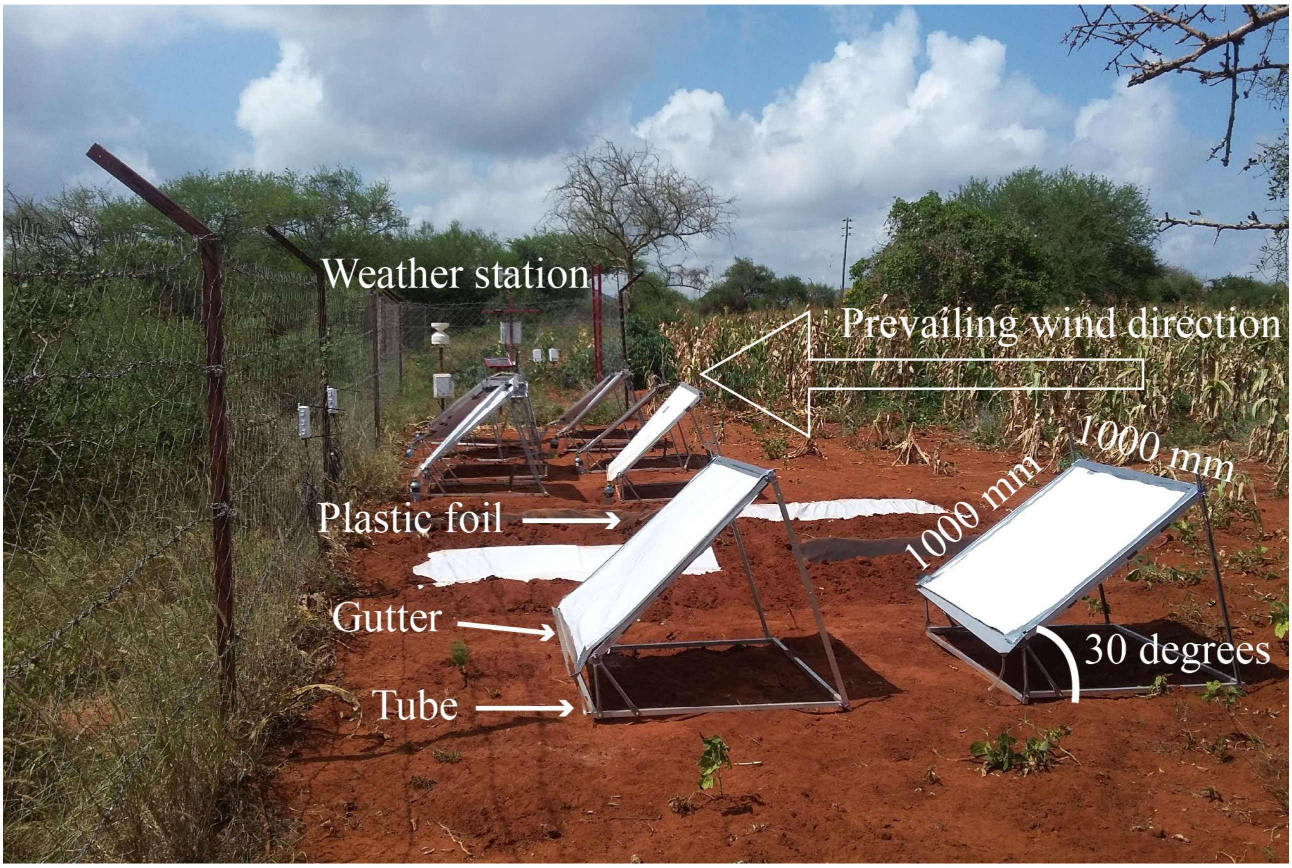

Figure 4. Setup of dew collection experiment in Maktau, Kenya, March 1-31, 2016. Photograph: Juuso Tuure, 2016.

The quantities of condensed dew were measured each morning at sunrise at approximately 06.00 AM, using a measurement vessel calibrated to an accuracy of 1 ml. The water remaining on the condensing surface was wiped, and the measured and reported water quantity was a result of the dew collected by both the gravity-induced flow and the wiping. Measurements and field work were carried out by trained staff of the Taita Research Station. There were 30 nights during the field experiment with notable dew. The one night with rainfall was excluded from the study. Otherwise, the night-time weather conditions remained consistent throughout the measurement period (Figs. 5 and 6).

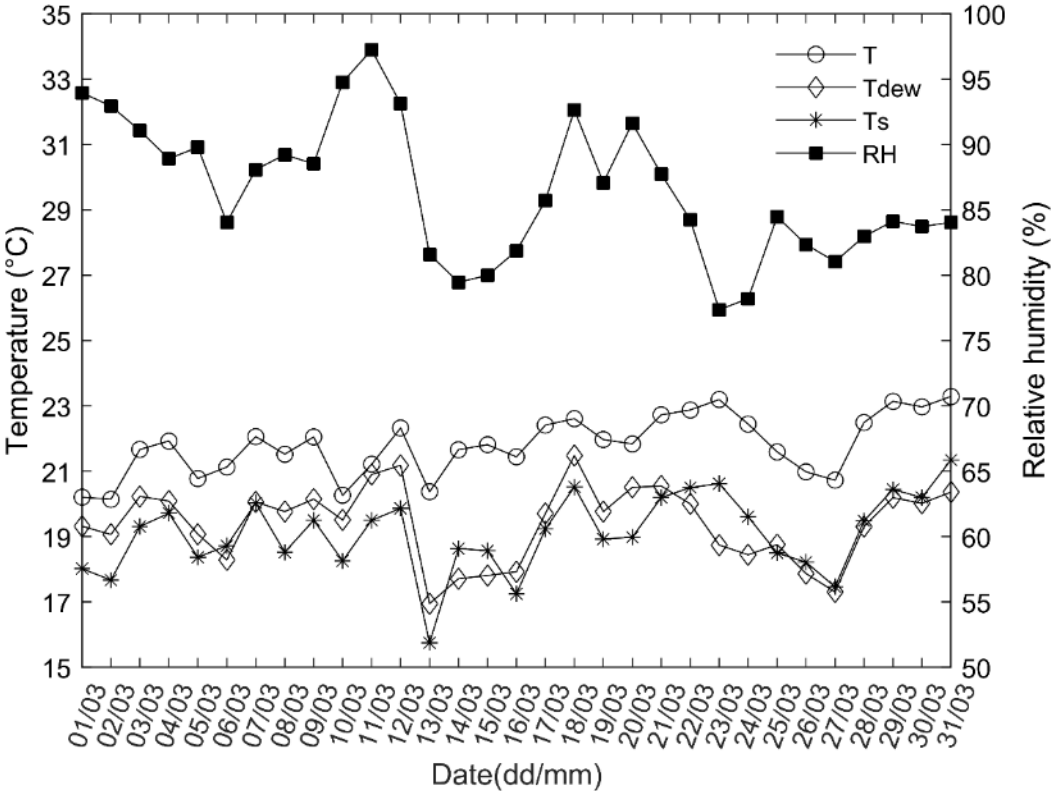

Figure 5. Night-time mean air temperature (T), mean dewpoint (Tdew), mean surface temperature of OPUR2 dew collector (Ts) and air relative humidity (RH) during the measurement period at the experimental field. As a definition of night-time, we considered the time when measured incoming net solar radiation was 0 W m^{-2} and thus the night-time occurred between 19:30 and 06:00.

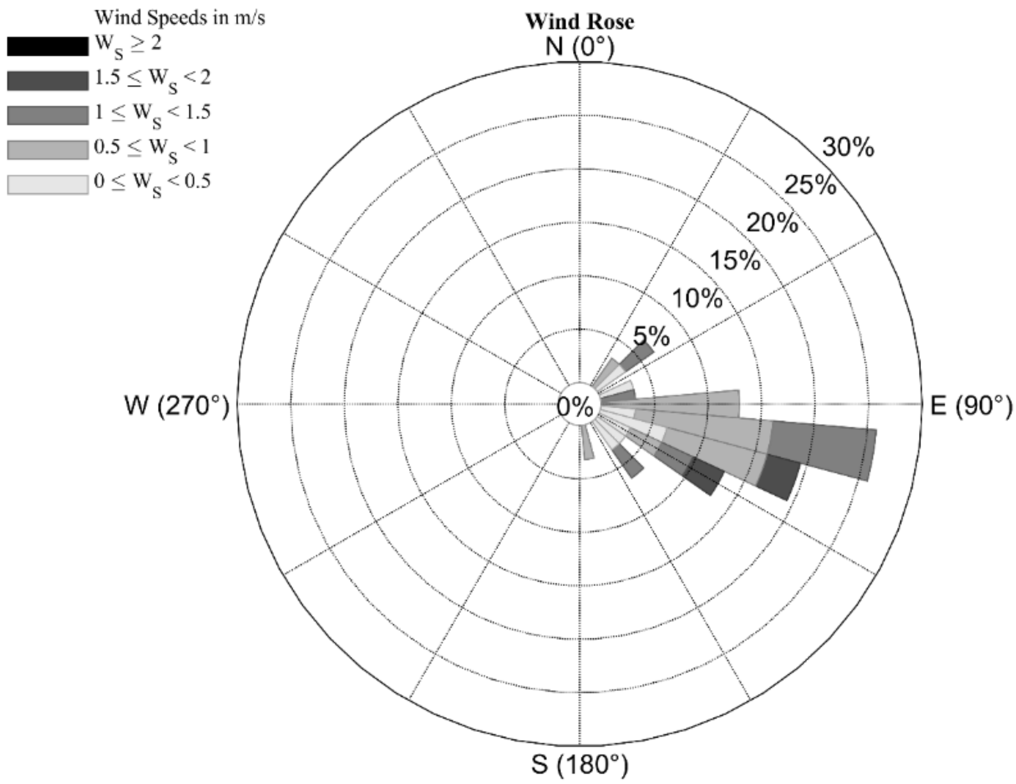

Figure 6. Wind rose displaying the distribution of the night-time winds (speed and direction) over the measurement period. Each concentric circle represents a different frequency at which winds occur. The night-time was between 19:30 and 06:00 (See Fig. 5 for definition).

2.4 Theoretically calculated dew yields for the laboratory experiments

The surface temperature of the dew-condensing surface, relative humidity of the air, air temperature, and air velocity were measured, to calculate dew output for the laboratory-setup with a diffusion model based on Fick's law presented earlier by (Tuure et al., 2019) and to compare these to the measured dew quantities. The purpose of the modelling was to evaluate the relationship between the actual measured dew quantity and the theoretical dew yields. The purpose of this comparison was to give confidence to the measurement setup, especially to the character of air movement in wind tunnel and i.e. to identify possible reasons for losses in the actually acquired water yields caused by surface characteristics of the dew collection foil and prevailing weather conditions. In practise, the calculations were done using MATLAB (MATLAB, 2018).

The dew condensation process can be presented as an equilibrium heat balance equation between various heating or cooling powers (Beysens et al., 2005; Nikolayev et al., 1996; Pedro & Gillespie, 1981; Vuollekoski et al., 2015):

$$\frac{dT_c}{dt}(m_c C_c + m_w C_w) = P_{rad} + P_{cond} + P_{conv} + P_{lat} \tag{1}$$

where T_c is the temperature of the condenser, C_c is the specific heat capacity (J kg^{-1}) of the condenser and C_w of water, m_c is the mass of the condenser and m_w of water. The right-hand side of the equation represent the powers (W) involved in the heat exchange. P_{rad} is the energy gain or loss due to radiation, P_{cond} describes the conductive heat flow to the surface. P_{conv} describes the convective heat exchange (sensible heat) term. P_{lat} in Eq. (1) is the energy that is released due to latent condensation of water:

$$P_{lat} = L_w \frac{dm_w}{dt} \tag{2}$$

where L_w is the latent heat of vaporisation, i.e. the latent heat released during condensation in this case. As we measured the temperature of the dew-condensing surface, air relative humidity, air temperature, and air velocity we can re-write the equation for the condensing rate (Eq. (2)) as a mass equation, i.e. Fick's law. Fick's law gives the mass flow, i.e. the diffusion of water vapour through the laminar layer at the surface, when temperatures and humidity at the surface and in the air along with the thickness of the laminar layer are known, dew output can be calculated as:

$$\frac{dm_w}{dt} = S_c D \frac{\left(p_{sat}(T_d) - p_c(T_c)\right)}{\delta} = S_c k\left(p_{sat}(T_d) - p_c(T_c)\right) \tag{3}$$

where mw is the mass (kg) of condensed water (dew), S_c is the surface area (m^2), D is the diffusion coefficient (m^2 s^{-1}), p_{sat} (T_d) is the saturation vapour pressure of water (Pa) at dew point, p_c

(T_c) is the vapour pressure of the condensation surface at temperature T_c, and k (m s^{-1}) is the mass transfer coefficient. Instead of the vapour pressures, the respective absolute humidity (x) in units (kg kg^{-1}) was used in our calculations:

$$\frac{dm_w}{dt} = S_c k(c_a - c_c) = S_c k \rho_a (x_a - x_c) \tag{4}$$

where c_c is water concentration (kg m^{-3}) on the condensing surface and ca is water concentration in ambient air. If $c_c > c_a$, the mass flux is negative and evaporation occurs. However, this applies only if there is accumulated dew on the condensing surface. This did not occur during our measurements, as the conditions were set to favor condensation. c is replaced with x and ρ_a is the density of air (kg m^{-3}). It was assumed that the relative humidity of air on the condensing surface was 100%. This may not always be the case, but this assumption was made to calculate the upper limit of condensation. The value of x_c is known because the surface temperature was measured. The x_a term was similarly obtained from the measured ambient temperature and air relative humidity.

A mass transfer coefficient k in dimensional analysis was used instead of a boundary layer thickness (δ). The mass transfer coefficient k is obtained from:

$$k = Sh\frac{D}{L_c} \tag{5}$$

where Sh is Sherwood's number, D is the diffusion coefficient, and L_c is the characteristic length of the condensing surface. The value of D represents the diffusion of the vapour in air and is temperature dependent. For D the value 2.49 x 10^{-5} m^2 s^{-1} at 20 °C was used (Monteith &Unsworth, 2013). In this case, Sh is unknown. It was assumed that the thickness of the laminar layer of heat transfer is similar as in the mass transfer, and by similarity Sh can be replaced with Nusselt's number (Nu) and Eq. (5) can be re-written as:

$$k = Nu\frac{D}{L_c} \tag{6}$$

According to Monteith and Unsworth (1990), for a flat plate in laminar flow ($Re < 2 \times 10^4$) Nu is:

$$Nu = 0.60Re^{0.5} \tag{7}$$

where Re is Reynold's number and can be calculated in a flat plate case as:

$$Re = \frac{vL_c}{\nu} \quad (8)$$

where v is the velocity of the fluid (air), L_c is the characteristic length or hydraulic diameter and ν is the kinematic viscosity of air at 27 °C is 1.57×10^{-5} $m^2 s^{-1}$ (Pitts and Sissom, 1977).

2.5 Statistical analyses

For the measured laboratory data, the variables normality was tested. Data normality allowed the use of parametric tests. The mean ranks for dew yields measured in laboratory with different plastic foils were also compared with a post-hoc test. The distributions of the dew yield data recorded in field were found to be non-Gaussian and a non-parametric test was used for evaluation.

3. Results

3.1 Laboratory measurements: Evaluation of location impact on dew yield

Ten measurements were initially carried out on OPUR foil (Table 3) to evaluate the impact of the condensing surface location within the climate chamber. The model was also evaluated by comparing the theoretically calculated values with the measured values for both condensing surfaces. The evaluation of the impact of the condensing surface location within the chamber was done using parametric Student's two-sample t-test (MATLAB, 2018, The MathWorks, Inc.) after the distributions of the data variables had been found normally distributed ($p > 0.05$) using Shapiro-Wilk's test (IBM SPSS statistic software 2014). The evaluation uncovered a statistically significant difference between the condensing surfaces (S1 and S2). This indicated that the location of the condensing element within the climate chamber impacted both the measured ($p < 0.05$) and calculated ($p < 0.05$) dew yields. For the 10 verification measurements, statistically significant difference were found between the dew yields for the measured and calculated values for S1 ($p < 0.05$) and S2 ($p < 0.05$).

Table 3. Statistical descriptives of the 10 measurements performed on OPUR foil on both condensing surfaces (S1 and S2). The values are in mm.

Descriptive	S1 measured	S1 calculated	S2 measured	S2 calculated
Mean dew yield	1.62	1.38	1.28	1.56
Mean Standard error	0.05	0.03	0.05	0.03
95% Confidence Interval				
Lower bound	1.51	1.30	1.17	1.49
Upper bound	1.73	1.45	1.39	1.63
Median	1.66	1.42	1.33	1.54
Variance	0.03	0.01	0.03	0.01
Standard deviation	0.16	0.11	0.16	0.10
Minimum	1.25	1.20	1.05	1.45
Maximum	1.82	1.51	1.47	1.76

3.2 Laboratory measurements: Evaluation of the plastic foils

Dew was collected with each plastic foil tested in the laboratory. The mean measured dew quantities were higher than the mean theoretically calculated quantities for OPUR and PEB for S1 (Fig. 7a) and PEB for S2 (Fig. 7b). Also, the mean theoretically calculated dew quantities were higher than the measured quantities.

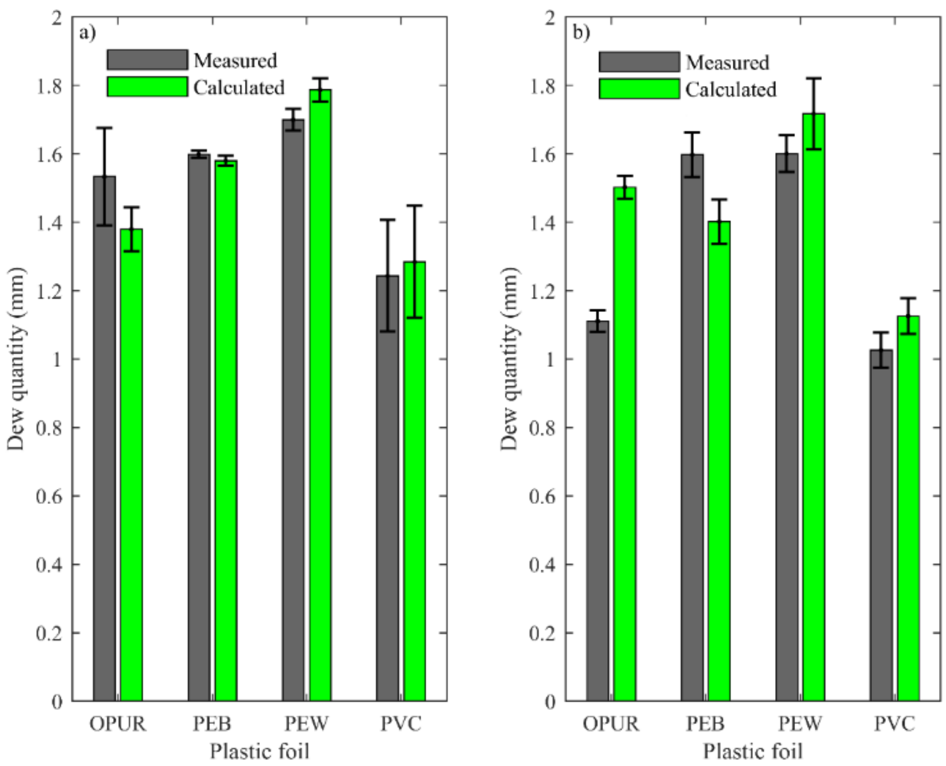

Figure 7. Measured and calculated dew yields for the tested plastic foils (See Table 2 for definition) as a mean of three measurements with the condensing surfaces S1 (a) and S2 (b) in the laboratory set-up. Measurement time four hours. Error bars illustrate the standard error of the mean as a ± segment.

One-way ANOVA test (MATLAB, 2018, The MathWorks, Inc.) was performed separately on the dew yields measured for S1 and S2 as we found out that the location of the condensing surface had an impact on the dew yields. The test indicated that the difference in dew yields measured with the plastic foils on condensing surface S1 did not statistically significantly ($p > 0.05$) differ from each other. Statistically significant differences existed for S2 ($p < 0.05$). Post-hoc Tukey's test (MATLAB, 2018, The MathWorks, Inc.) showed that the S2 mean dew yields measured with OPUR and PVC were significantly smaller than the mean dew yields measured with PEB and PEW ($p <0.05$) (Fig. 8).

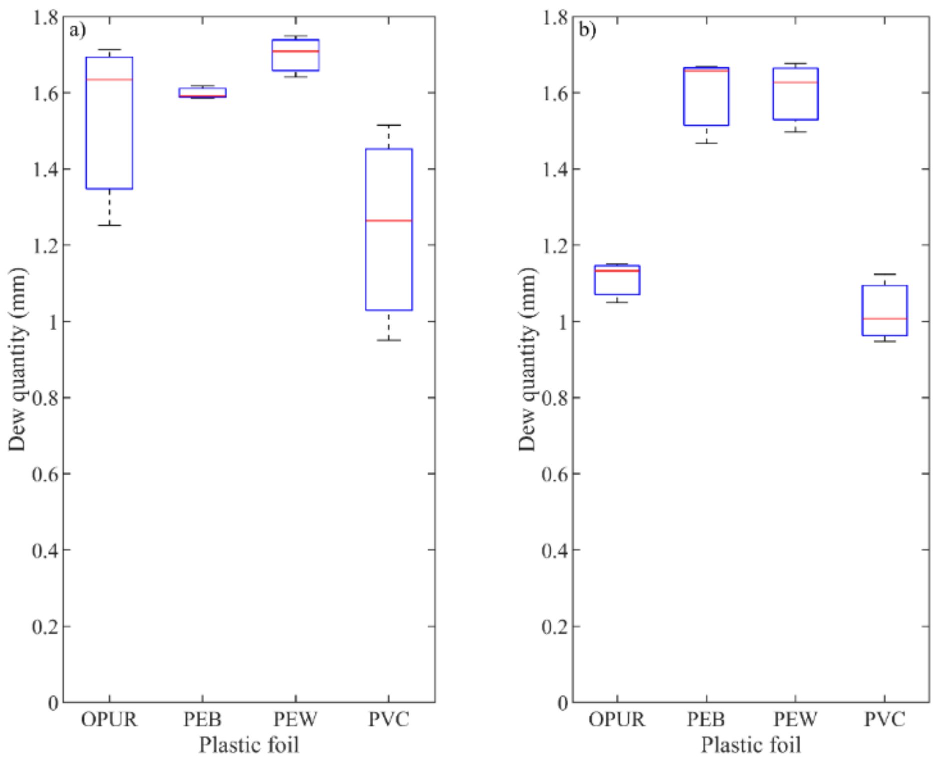

Figure 8. Comparison of the dew yield means measured with different plastics for condensing surfaces S1 (a) and S2 (b) as a boxplot showing the median or the 50% quantile (red line), where the bottom and top edges of the box indicate the 25% and 75% quantiles, respectively. The maximum whisker lengths are 5% and 95% range.

3.3 Performance of the plastic foils in field conditions

During the measurement period, notable dew events occurred during 30 nights, whilst rainfall occurred only during one night. Collectors coated with PVC and OPUR performed best during the field tests regarding dew collection efficiency (Fig. 9). The collected dew quantity varied greatly from night to night, which is evident from the large standard deviations of nightly measured dew (Fig. 9) and from the distributions of the measured dew yields (Fig. 10). In the field conditions potential condensing times during nights with recorded dew spanned from 0.5 to 11 h, lasting on average 5.5 – 8.0 h (Table 4).

Table 4. Mean, max and min time periods (h) when measured surface temperatures were below the dew point and amount of nights when dewfall was recorded (N). Data is presented for the four of the eight dew collectors, which measured surface temperature time series did not have any gaps in the measurement data. See Table 2 for definition of plastics and Fig.3 for dew collector location.

	OPUR2	PEB1	PEB2	PEW2	PVC1
Mean	8.0	7.1	5.5	6.1	7.4
Max	11.0	10.5	10.0	11.0	10.5
Min	5.0	2.5	0.5	1.0	2.5
N	26	27	25	29	29

The highest dew yield during one night was recovered with a collector covered with OPUR (0.252 mm). The lowest yields recorded were 0.001 mm (OPUR and PVC). According to the non-parametric Kruskal-Wallis test performed, no statistically significant differences occurred between the mean ranks of the dew yields measured with the dew collectors coated with different plastic foils ($p > 0.05$).

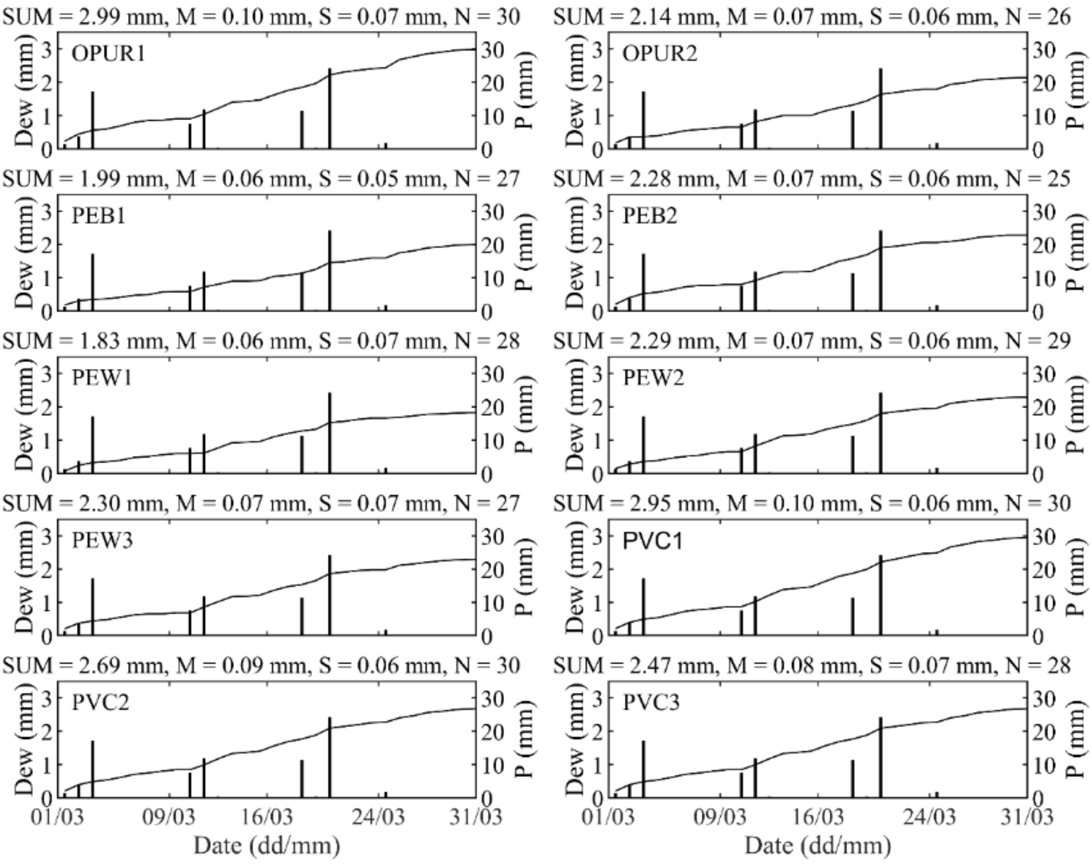

Figure 9. Measured cumulated dew yields (lines) for all collectors and precipitation events (bars) during the 31-day measurement period March 1–31, 2016 in Maktau, Kenya. In the figure, P stands for precipitation, SUM for total cumulated dew sum during the measurement period, M for nightly mean dew quantity, S for standard deviation of nightly dew and N for amount of days with dew during the measurement period. See Table 2 for definition of plastic and Fig. 3 for dew collector location.

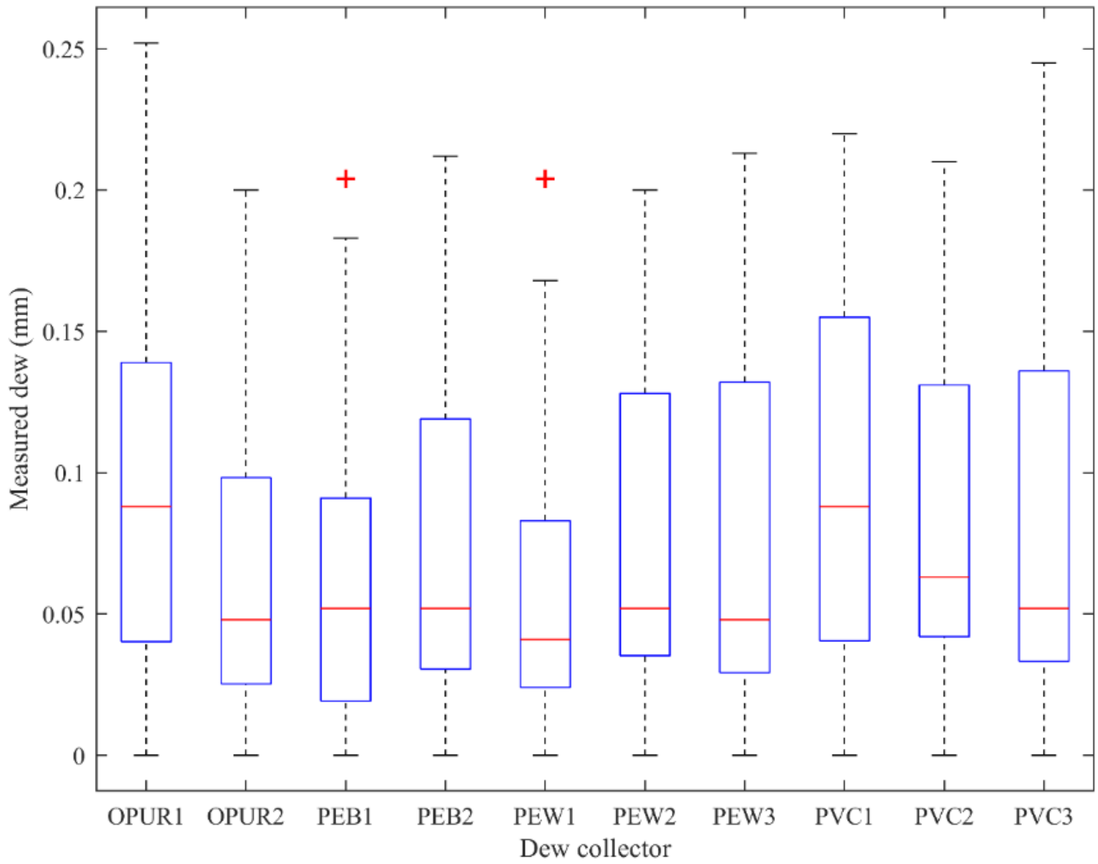

Figure 10. Distributions of the daily dew yields of the different dew collectors (Fig. 3). The horizontal lines within the box represent the medians (50% quartiles), while the 25% quartiles are shown by the lower ends of the central boxes and the 75% quantiles by the upper ends of the central boxes. The maximum whisker lengths are 5% and 95% range. Outlier data points are displayed using "+". See Table 2 for definition of the plastic foils.

4. Discussion

We were able to harvest dew in laboratory conditions using the hardware model constructed for the purpose. All of the tested plastic foils gave measurable dew yields. The location of the condensing surface (Peltier element) within the laboratory setup significantly impacted the dew yield, and therefore the results for both condensing surfaces (S1 and S2) had to be analysed separately.

No similar dew collection experiments performed using hardware models in laboratory conditions are reported in the literature. Rather than focussing on the absolute quantities, our focus was on comparing the dew-harvesting efficiency of the plastic foils. Comparing the dew yields measured with other hardware models would also be difficult because the condensing rates (ml h^{-1}) of the hardware models are affected by the cooling power of the condensing elements and by the temperature and relative humidity of the ambient air in the climate chamber.

A notable deviation was observed in the repeatability and reproducibility of the three measurements with all of the tested surface materials and between the 10 verification measurements. The variation was potentially due to the small area (40 x 40 mm^2) of the condensing Peltier element and also due to the small quantities of collected dew, which resulted in a single droplet potentially having a significant impact on the measured dew yield making it difficult to reach accurate valid conclusions. Nevertheless, the results could be interpreted as a comparative study between the foil materials.

The highest mean dew yields in the laboratory were measured from the PEW foil. The second-best yield was measured from PEB followed by OPUR and PVC, respectively. The high standard deviation of the dew yield for OPUR measured in the laboratory may be due to the variation in the contact angle (Table 2) within the foil. The high variation did not reflect on the calculated dew quantities, which suggests that the variation was not caused by the varying conditions such as temperature, relative humidity, or airflow.

OPUR and PVC dew yields were statistically significantly smaller than PEW and PEB dew yields. The results measured in the laboratory did not reflect the results measured in the field experiments. No statistically significant differences were observed between the different plastic foils during the one- month experiment period in the field experiments in Kenya.

The highest dew yields in field conditions were measured with OPUR1. However, no statistically significant differences occurred between the tested plastics. The dew yields, which we were able to harvest in the field measurements (Fig. 8), were in line with those reported in other field studies performed with similar dew collectors and OPUR. Average dew quantities per dew event found in the literature span from 0.069 to 0.145 mm per dew event (Clus et al., 2008; Jacobs et al., 2008; Maestre-Valero et al., 2011; Muselli et al., 2002, 2009; Nilsson, 1996). Only a few dew collection studies have reported on other plastic foils than OPUR. The average dew yields span from 0.073 to 0.128 mm per dew event (Arias-Torres & Flores-Prieto, 2016; Beysens et al., 2007; Maestre-Valero et al., 2011; Nilsson, 1996; Nilsson & Niklasson, 1995; Sharan et al., 2007).

The results measured in the laboratory environment did not reflect on the results measured in field conditions using the same plastic materials. The laboratory measurements were performed in controlled conditions with air humidity consisting of vaporised distilled water, and these laboratory- measured results will very likely not apply in field conditions, as we discovered. In field conditions, contaminants, i.e. dust particles, impurities etc., are present in the ambient air. They affect the wetting angle of the surface (Beysens, 1995), thereby affecting the condensation and gravity-induced flow of the dew droplets condensed on the surface. The radiative cooling effect of the night-time sky is another key factor affecting the collected dew yield in the field conditions (Jones, 2014; Monteith, 1957; Revankar, 2009). The effect of the surface emissivity (in the IR region), which affects the cooling quality, was not evaluated in our study. Contaminants, however, are very likely affect the thermal radiation quality of the surface (Beysens, 1995). The conditions in field are therefore likely to equalise the differences between the different materials.

Our aim was to build a system that tests the suitability of plastics for dew collection and ranks plastics dew collection ability instead of performing laborious tests in the field. Conditions like field conditions are challenging, if not impossible to recreate them with a laboratory setup. Steady state conditions were chosen for reproducibility. The chosen operating conditions are close to the average conditions in field, but the narrow range of operational conditions sets limits on the conclusions that can be drawn from the results of our study. For future steps regarding the development of a laboratory scale dew measurement setup, we suggest including a broader design of experiment, that would cover a wider range of operating conditions, similar to temperature, air relative humidity and air flow conditions occurring in field. It would also be useful to include laboratory measurements for condensing surface angles less than 90° as being more like real dew collectors used in field conditions i.e. the utilising the commonly used 30° angle. The use of larger condensing surfaces than presented in this study is also recommended. The amount of dew water accumulated on larger surfaces is higher and the amounts to be measured would then not be unnecessarily small. This would make it easier not only to measure the amount of water, but also to detect differences between the different plastic surfaces.

Our theoretical calculations, based on the measured surface temperature of the plastic and ambient conditions, showed a similar trend regarding the differences between the plastic foils. The model calculations were considered to have functioned well in evaluating the rankings of the different plastic foils in laboratory conditions. However, according to our results, the calculations cannot be used to precisely estimate dew quantities, as the quantities measured with OPUR for the laboratory set-up were statistically significantly different from the theoretically calculated dew quantities for both S1 ($p < 0.05$) and S2 ($p < 0.05$).

The greatest uncertainty in the theoretical calculations of the dew yields was caused by the unknown character of the airflow in the wind tunnel. The wind tunnel inlet fan mixed air and inherently caused turbulence since there was no honey-comb to stabilise the air flow. The *Re*-number was calculated using Eq. (8) for a square duct with the side length and hydraulic diameter 105 mm. The *Re*-numbers for the measured airflow 1.70 and 2.15 m s^{-1} were 11300 and 14400 respectively, indicating the tubular airflow in the wind tunnel was within the turbulent range (i.e. $Re > 2300$). On the other hand, the Peltier-elements were mounted away from the wall of the wind tunnel and thus air movement at the condensing surfaces could have been laminar. Calculating the *Re* for a flat plate, and using the measured horizontal air velocities at the surfaces of Peltier-elements of 1.70 m s^{-1} and 2.15 m s^{-1}, resulted in *Re* values of 4300 and 5500 respectively, which were well within the laminar flow regime for a flat plate ($Re < 2 \times 10^4$). Calculations for mass transfer assuming turbulent tube flow in the wind tunnel and at the condensing surface (flat plate) were also carried out. These calculations showed values that were also in strong contradiction to the measured dew values.

Surface temperature measurements also caused uncertainty in the model calculation. It proved difficult to reliably measure the temperature of the condensing surface with the thermocouples in a way that could represent the temperature of the entire surface. This probably is the reason why the theoretically calculated dew quantities were occasionally less than those measured. Also, the formation of dew droplets heats the surface when latent heat is released, causing local temperature variation on the measured surface but the single point measurement was assumed to represent the entire surface temperature, which may not always be the case. Another implementation method is therefore recommended for acquiring surface temperature when performing similar measurements.

It should be pointed out that dew harvesting is a promising method to improve agricultural activities and food security in rain-fed arid and semi-arid areas of sub-Saharan Africa, where significant amount of dew occurs. After the field experiments had ended, the local farmer in Maktau continued dew collection after the experiment and reported harvesting up to 2 l d^{-1} from 10 dew collectors (1 m^2). The farmer planted 10 mango trees (*Mangifera indica*) in his field and was irrigating them using the harvested dew water (Appendix Fig. A).

5. Conclusions

A hardware model for testing dew collection was constructed and used to test plastic foils, both in controlled laboratory conditions and in arid field conditions. Using model calculations, the ranking of the measured dew yields was predicted using the measured parameters. It was difficult to evaluate the dew-harvesting quality of plastic foils and coatings based on our laboratory test results since no clear similarity was found between the dew yield results of different foils measured in field conditions and the results performed under laboratory conditions. However, it should be noted that no statistically significant differences were found between the tested materials under the field conditions. A more comprehensive evaluation regime requires more specific tests performed in field conditions and further development of the design of the hardware model presented. The hardware model could also be developed more towards field conditions, including a broader range of operating conditions and e.g. radiative cooling and air contaminants

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 1. Weather conditions in Maktau. Daily mean values for temperatures (T) and air relative humidity-%, the number of sunny hours, and the accumulated precipitation during the period between August 31, 2014 and August 31, 2016

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Mean T (°C)	24.2	24.4	24.7	22.9	21.6	20.6	19.7	19.8	20.8	22.6	22.8	23.4	22.3
Mean T Min (°C)	18.5	18.2	18.4	19.0	17.1	15.7	14.5	14.6	15.2	16.9	18.1	18.7	17.1
Mean T Max (°C)	31.3	32.2	32.7	29.6	28.3	27.5	26.5	26.9	28.1	30.2	29.7	29.9	29.4
Mean precipitation (mm)	48 .3	4.1	57.0	108.8	33.2	7.6	9.5	4.3	14.0	28.9	108.0	58.9	40.2

Figure 1. Farmer irrigates 10 mango seedlings with the dew harvested.