Assessment of Airborne Transport of Potential Contaminants in a Wind Tunnel

Ivano Cornacchia[1]; Séverine Tomas[2]; Jean-Paul Douzals[3]; and Dominique Courault[4]

Abstract: The reuse of treated wastewater (TWW) for sprinkler irrigation could potentially diffuse pathogen-containing droplets off the application area. Wind and other unfavorable climatic factors enhance irrigation drift and bioaerosol dispersion, exposing humans to potentially severe health risks including the spread of diseases. Few studies have quantified bioaerosols during both spraying and airborne transport phases. Studies of effective sampling strategies to better qualify the dispersion process are also required. This paper presents experiments conducted in a wind tunnel for a deeper understanding of the effects of wind and temperature on pathogen or contaminant airborne dispersal and transport. It is the first time that passive collectors [polyvinyl chloride (PVC) lines] and active samplers (AGI-4 impinger) have been compared under analogous wind conditions using a fluorescent tracer. Droplet-size distribution was also investigated at 12 m from the boom with a NanoMoudi 122-NR cascade impactor in increasing wind conditions from 1 to 3 $\mathrm{m\,s^{-1}}$. PVC lines return a detailed evolution of the sprayed volume within a short range from the boom and for concentrated fluxes. Transport assessment of PVC lines indicates that transport and permanently airborne condition of the spray notably grow with increasing wind, resulting in a more compact and concentrated plume; mean transport increases from 0.13 to 1.18 $\mathrm{L\,h^{-1}\,m^{-2}}$ at 7.7 m from the nozzle as the wind velocity increases from 1 to 3 $\mathrm{m\,s^{-1}}$. AGI-4 appears more suitable to assess finely aerosolized conditions because of its greater sensitivity compared to PVC lines as shown for sample values less than 1 $\mathrm{L\,h^{-1}\,m^{-2}}$. The comparison between the AGI-4 and PVC lines shows higher values of recovery for the active samplers compared to the PVC lines. The total volume collected by the impingers was 2.93% of the sprayed volume, approximately twice that collected by PVC lines under analogous conditions, even though their sampling surface was only 1.54% that of PVC lines. Droplet-size distributions from the cascade impactor denote a median volume diameter from 1.1 to 2 μm, for the nozzle type used, and a relevant reduction in recovery at stronger wind velocities. An empirical relation *time of flight* is proposed as a first step in developing decision models that can be used to make sprinkler irrigation safe and to define standards for TWW reuse in agricultural practices (e.g., safe distance of application depending upon wind conditions and droplet-size distribution). **DOI: 10.1061/(ASCE)IR.1943-4774.0001423.**

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Introduction

The reuse of treated wastewater (TWW) for irrigation is a valuable solution for arid regions or during periods of water scarcity; however, it may diffuse aerosols containing infectious entities, such as bacteria and viruses of fecal origin (Teltsch and Katzenelson 1978). Numerous studies have shown the presence of residual contents of toxic pollutants and pathogens in wastewater even after the treatment process (Carducci et al. 2000; Petterson et al. 2001; Pachepsky et al. 2011). Normally, the population of microorganisms surviving in TWW undergoes a rapid decrease subsequent to deposition on soil (Pescod 1992). However, enteric viruses and noroviruses are often found in significant amounts because they are not fully eliminated by standard treatments (La Rosa et al. 2010; Cheng et al. 2012; Courault et al. 2017).

A human health hazard may originate from water-atomizing devices, such as sprinklers, that may diffuse pathogen-containing aerosols into the surrounding environment. Water droplets provide shelter and protection from temperature shocks and sunlight exposure, increasing the chances of pathogen survival and preserving infectivity (Tyrrell 1967; Donnison et al. 2004; Teunis et al. 2010; Colas de la Noue et al. 2014). Inhalation of pathogenic aerosols could lead to severe pulmonary inflammation or potential outbreak of disease (Hickey and Reist 1975; Cangialosi et al. 2008; Stellacci et al. 2010; Chang and Hung 2012).

There is evidence of unsafe bioaerosol emissions from wastewater treatment plants, constituting a severe risk for exposed workers and habitants in their surroundings (Filipkowska et al. 2000; Heinonen-Tanski et al. 2009; Korzeniewska 2011; Masclaux et al. 2013). However, very few studies have reported that sprinkler irrigation with TWW could similarly present a potential source of emission of infectious and inhalable bioaerosols. In early studies, Bausum et al. (1983) assessed that airborne bacteria were detectable up to 200 m from the source of application, from experiments conducted with sprinklers and a wind velocity between 2.7 and 3.4 $\mathrm{m\,s^{-1}}$. However, this phenomenon is poorly understood and suffers from scarce literature and data.

Particle size has a large influence on dispersion because it determines the interactions with air currents and the capability to

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access the human respiratory system. Airborne particles greatly vary in size, approximately within a range from less than 0.3 to 50 μm or greater (Amato et al. 2007). It is difficult to individuate the characteristic size of a wet bioaerosol: the inferior threshold is limited to the dimension of the pathogen itself, generally from 0.02 to 0.3 μm for single viruses and from 0.2 to 30 μm for bacteria, but there is no actual higher limit to their diameter because it depends on the droplet size. Moreover, weather conditions largely contribute to aerosol formation, and wind is the main driver causing water droplets to run off the area of application. Very small particles (i.e., nanometric and micrometric) and pathogens manage to travel for many kilometers before readily infiltrating human lungs (Donaldson et al. 1982; Papke and Ward 2004). Size distribution is the outcome of the combination of numerous parameters such as the weather conditions (temperature, relative humidity, and wind and solar radiation), sprinkler technology, and atomization process (Gantzer et al. 1998; Hogan et al. 2005; Dumouchel 2008; Stevenin et al. 2016).

Sprinkler irrigation delivers conspicuous quantities of fine droplets; thus, irrigation using TWW could be hazardous if pathogens or toxic contaminants are uncontrollably diffused into the environment. The kinematics of large droplets can be described with a ballistic model, but for smaller diameter droplets cases (<0.9 mm), only a partial agreement is found (Lorenzini 2004). As a matter of fact, sprinklers' droplet distributions are less likely to be characterized below the millimeter scale. Additionally, diffusion and evaporation of fine droplets from sprinklers (smaller than 100 μm) are poorly analyzed in the literature (Molle et al. 2012). It is even more difficult to predict the initial diameter of an aerosol when escaping the emission area, particularly for field experiments with unpredictable and unstable meteorological conditions and for pathogens encased in droplets, whose diffusion may occur in a manner different from what their size would suggest. Bioaerosol quantification under field conditions is difficult because too many different factors are considered for characterization (Verreault et al. 2008). Most studies dedicated to aerosol sampling are performed indoors, with a particular emphasis on collection efficiency (Griffiths et al. 1997; Dart and Thornburg 2008; To et al. 2008; Kang et al. 2012) and pathogen viability subsequent to sampling stress (Ge et al. 2014; West and Kimber 2015). Much fewer studies have focused on field sampling and dispersion of pathogens using TWW (Brooks et al. 2004).

Airborne displacement of fine droplets is a recurrent subject of study for sprinkler irrigation and pesticide drift, generally to evaluate the impact of air currents and the efficacy of sampling methods. Although the phenomena have several analogies, they differ in their sampling strategies and in the definitions provided to the effects of wind. In sprinkler irrigation, there is a difference in identification between drift and transport. ISO-15886 (ISO 2011) for irrigation defines drift as the difference in rainfall volume within the wetted perimeter under windy and nonwindy conditions. Only a precipitation rate greater than 0.3 $\mathrm{mm\,h^{-1}}$ (equivalent to 0.3 $\mathrm{L\,h^{-1}\,m^{-2}}$) is considered valid for drift measurement. The volume of water less than this threshold is defined as transport water (aerosolized part). To quantify transport, ordinary rain gauges are not suitable; thus, alternative sampling strategies able to detect minute amounts of airborne material have to be implemented, such as those adopted in pesticide studies (Molle et al. 2016). ISO-22866 (ISO 2005) for crop protection defines drift as the quantity of product (i.e., pesticides) that is carried off the sprayed area by the action of wind during the application process. Pesticide drift assessment is characterized by robust methods for airborne sampling, commonly centered on the interception of the spray through thin horizontal polymeric lines. However, in pesticide drift no distinction is assumed between drift and transport.

Numerous parameters have been identified in pesticide drift (Al Heidary et al. 2014): the effect of wind velocity has been extensively investigated in relation to the nozzle type (Nuyttens et al. 2007a; Miller et al. 2008; Nuyttens et al. 2009; Ferguson et al. 2015), physiochemical properties (Miller and Ellis 2000; Miller 2003; Spanoghe et al. 2007; De Schampheleire et al. 2009), and spray unit configuration (Murphy et al. 2000; Nuyttens et al. 2007b; Miller et al. 2011). Several collection methods to characterize drift have been developed using commercialized passive collectors (e.g., monofilament lines, filter papers, and Petri dishes) or active collectors such as rotating devices (Clayson et al. 2010; Farooq and Walker 2014). Wind tunnel experiments have significantly contributed to drift assessment because they permit controllable and repeatable conditions. Various wind tunnel protocols have been introduced for pesticide drift assessment, meeting ISO 22856 (ISO 2008) requirements, with the use of horizontal polymeric lines and a fluorescent tracer. The two most representative are local environment risk assessment for pesticides (LERAP) (Andersen et al. 2000; Gilbert 2000; Walklate et al. 2000) and drift index (DIX) (Herbst and Ganzelmeier 2000). Currently, no similar studies have been conducted to analyze transport from TWW irrigation. In the framework of irrigation using TWW, sampling methods are currently not defined by structured protocols because this topic is relatively new, in contrast to pesticide drift and indoor bioaerosol sampling. Thus, the general aim of this study was to investigate the effects of wind and temperature on airborne transport and to compare different collection methods. This study aimed to contribute to a preliminary examination by comparing different sampling methods under controlled air conditions and to validate their use for future applications using actual TWW. The aim of this study was to define a robust protocol to quantify airborne transport during irrigation.

Three more specific objectives were targeted in this study as follows: (1) an analysis of the effects of wind and temperature on airborne transport using horizontal PVC lines; (2) a comparison of the collection of active and passive samplers, AGI-4 and PVC lines respectively, under analogous conditions; and (3) a characterization of droplet size under very diluted conditions using a cascade impactor and the performance of the collector under increasing wind. The long-term prospect is to develop a more robust approach for field sampling and to provide useful information in terms of distance and wind velocity to ensure the safety of use of sprinklers using TWW.

Materials and Methods

The experiments were undertaken in a wind tunnel (with a relative humidity >90% to reduce the effects of evaporation) and with the use of a fluorescent tracer for sampling. Each setup was organized into three phases: (1) first, a water-tracer solution was deployed from an external air-pressurized tank, connected to the spray generator unit of the wind tunnel; (2) then, samples were collected and analyzed; and (3) finally, the quantity of water on the sampling surfaces was computed.

Wind Tunnel

The wind tunnel at IRSTEA-ITAP (National Institute for Environmental and Agricultural Science and Research joint research unit for Information and Technologies for Agricultural Processes, Montpellier, France) (IRSTEA-ITAP 2011) was used for the three experiments described in the next section (Douzals et al. 2016). The tunnel is a closed-circuit system with a net working section 3 m wide, 2 m high, and 12 m long, capable of generating a wind velocity up to 12 $\mathrm{m\,s^{-1}}$, air temperature up to 40°C, and various


(a) (b) (c) (d)

Fig. 1. (a) Thermometer of the tunnel; (b) anemometer of the tunnel; (c) inside view of the wind tunnel, spray boom, and PVC line installation for the airborne transport assessment; and (d) pressurized tank containing the water and tracer solution.

levels of humidity including saturation. The temperature was measured using a Pt100 gauge (Corrège, Chaignes, France) (±0.3°C) and the wind velocity was recorded using a WindSonic two-dimensional sonic anemometer ($\pm 0.2\ \mathrm{m\,s^{-1}}$) (Gill Instruments, Lymington, UK) as shown in Figs. 1(a and b). An automatic control unit operating on the heating/cooling system and on the fan's rotational speed regulated the air parameters.

Spray Generator Unit

The use of a real irrigation sprinkler would be hardly feasible in such a small wind tunnel and the combined effects of axis rotation and drive arm might alter considerably the size distribution. Additionally, the intent was to recreate an air-carried droplets flow, independent from the sprinkler configuration but likely to be found when irrigating crops with a sprinkler at great distances from the sprinkler itself. Thus, to directly obtain drift-like droplets, the nozzle for greenhouse humidification (fogger) Coolnet PRO 7.5 Simple (Gill Instruments, Lymington, UK) was selected for the experiments. Foggers produce exactly the range of particles of interest for atmospheric transport in sprinkler irrigation (i.e., $<100\ \mu\mathrm{m}$).

The spray generator unit [Fig. 1(c)] was composed of a horizontal boom placed 1 m above the ground and equipped with four foggers horizontally oriented and spraying in the downwind direction. The spray generator was activated using a manual on/off valve at the tank outlet [Fig. 1(d)]. The operational pressure was fixed at 300 kPa and controlled using a Keller 33X pressure gauge (±1 kPa) (Keller, Winterthur, Switzerland) located in front of the nozzles. The droplet-size distribution of the nozzle at this given pressure was characterized by a volume median diameter of $110\ \mu\mathrm{m}$ ($\pm 1.7\ \mu\mathrm{m}$) measured using a Malvern Spraytec laser diffraction sensor (Malvern Panalytical, Malvern, UK).

Very fine droplets, less than $50\ \mu\mathrm{m}$, remain suspended in air indefinitely although they tend to rapidly evaporate; droplets greater than $200\ \mu\mathrm{m}$ are less affected by wind velocity and evaporation because of their larger volume. Most of the risk originates from those with intermediate characteristics; droplets sized between 100 and $150\ \mu\mathrm{m}$ are generally recognized as the most likely to drift, and they constitute the main hazard to human health (Hofman et al. 1986; Grisso et al. 2013).

Fluorescent Dye Tracer

Brilliant Sulfo Flavine (BSF) (Waldeck GmbH and Co. KG, Münster, Germany) was selected as a tracer for this study. Cai and Stark (1997) studied the performances of different fluorescent dyes and selected BSF as the most suitable to assess spray drift because its degradation is only 11% after 8 h of sunlight exposure and its lowest limit of quantification with a spectrofluorometer is approximately $10^{-6}\ \mathrm{g\,L^{-1}}$.

Unlike water, the tracer remains on the collectors and does not evaporate, allowing indirect evaluation of the corresponding transport. After deposition of BSF on the PVC lines, or aluminum plates of the cascade, sampling surfaces were collected from the working section only when the water was fully evaporated to avoid dripping. In the AGI-4 setup, this was not possible because the captured droplets diluted into the liquid contained in the flask. Sampling surfaces were, hence, rinsed with a known volume of demineralized water and analyzed using a Perkin Elmer LS 45 fluorometer (PerkinElmer, Waltham, Massachusetts). The excitation and emission wavelengths for the BSF used during the fluorescence analysis were, respectively, 450 and 500 ± 10 nm. The optimal range of accuracy was individuated within the linear trend of the read values in fluorescence intensity, between 5 and $450\ \mu\mathrm{g\,L^{-1}}$ of the BSF concentration, and verified using a fluorescence-concentration calibration curve. The limit of quantification was considered as twice the standard deviation of a blank sample (i.e., a sample containing only demineralized water) and it corresponded to a value of $1.5\ \mu\mathrm{g\,L^{-1}}$. At greater than $450\ \mu\mathrm{g\,L^{-1}}$, the measurement deviated from the linear trend and gradually approached saturation; therefore, a dilution of the sample was required. The initial concentration of BSF was adjusted depending on the sampler's constraint: $0.13\ \mathrm{g\,L^{-1}}$ for the PVC lines and $0.3\ \mathrm{g\,L^{-1}}$ for the AGI-4 and cascade impactor.

Experimental Setups

Setup 1: Effects of Wind Velocity and Temperature on Airborne Transport Using PVC Lines

Setup 1 [Fig. 2(a)] relied on a set of passive horizontal PVC lines (Plastelec, Ambert, France) because it is widely recognized as a nonintrusive approach for drift studies because the disturbance of airborne fluxes is minimal (Herbst and Molnar 2002). PVC lines are passive collectors but may collect a wide range of liquid droplet sizes from 50 to $200\ \mu\mathrm{m}$ (Gil et al. 2007). The proposed setup was inspired by the pesticide drift protocols LERAP and DIX. The first aim was to identify the maximal distance for relevant ground deposition; thus, measurements were taken throughout the length of the wind tunnel. The second aim was to evaluate the initial airborne drifting volume of water on a vertical array of horizontal wires. Both pesticide drift protocols consider performance with reference to a benchmark level/nozzle to simplify and standardize nozzle

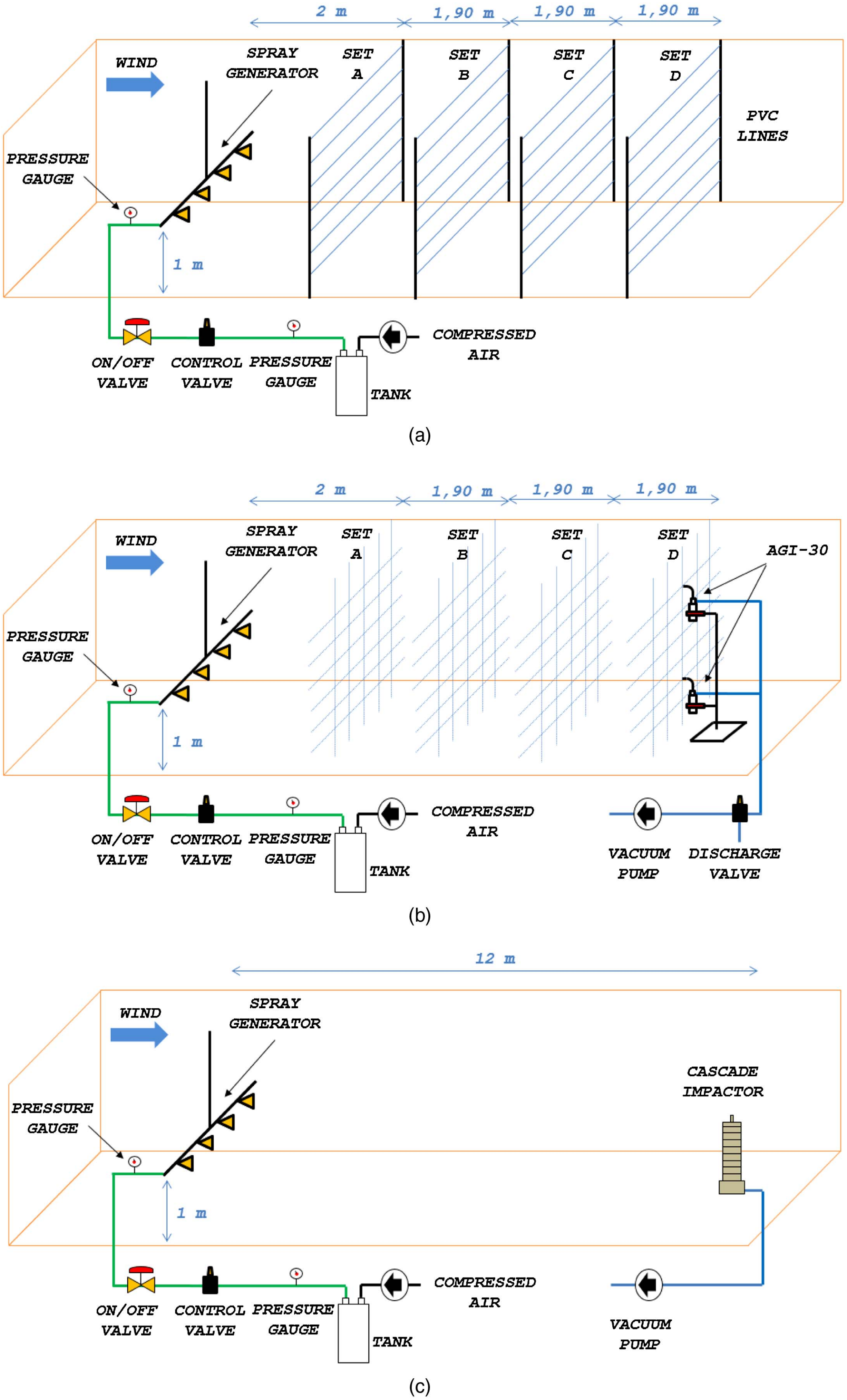


Fig. 2. (a) Scheme of Setup 1: Four arrays of seven horizontal PVC lines each were installed in a wind tunnel to assess the evolution of a spray plume via the interception of a water-tracer solution; (b) scheme of Setup 2: similar to Setup 1, two AGI-4 biocollectors were placed in the tunnel and fixed on a vertical rod to reproduce a grid of 120 acquisition points for airborne transport assessment; and (c) scheme of Setup 3: a cascade impactor downwind of the spray generator unit was used to evaluate the droplet size distribution under finely aerosolized conditions.

performances. This study did not focus on drift mitigation of a specific nozzle type, but aimed to characterize the influence of wind and temperature on airborne transport.

The sampling grid of horizontal PVC lines was assembled downwind of the spray generator unit to intercept the solution of water and BSF as shown in Fig. 1(a). Four vertical arrays of horizontal sampling wires were placed downwind at 2, 3.9, 5.8, and 7.7 m from the boom and were associated with, respectively, the letters A, B, C, and D. Each array was composed of seven PVC lines 2 mm in diameter and 2.73 m in length. Each line was vertically spaced 0.25 m one from the other and from the ground.

Transport was assessed using a solution containing 0.13 $\mathrm{g\,L^{-1}}$ of BSF under nine different conditions with the wind at 1, 2, and 3 $\mathrm{m\,s^{-1}}$ and the air temperature at 15°C, 25°C, and 35°C for each velocity. Spray generation time was 10 s to avoid saturation of the wires and dripping, as recommended in the drift protocols.

Setup 2: A Comparison of Transport Recovery Using AGI-4 and PVC Lines under Low Wind Velocity Conditions

Setup 2 [Fig. 2(b)] aimed to compare recovery from passive and active collectors. The AGI-30 glass impinger is a common device for verifying the presence of one or more specific pathogens, especially for indoors cases (Tseng and Li 2005; Springorum et al. 2011; Zhao et al. 2011; Chang and Hung 2012). However, this study sought to achieve a more quantitative analysis by measuring a flux of air-carried droplets and by verifying the adaptability of the collector to windy conditions and thus for further in situ studies. For this experience, the AGI-4 glass impinger (Ace Glass Incorporated, Vineland, New Jersey) was adopted because it was already tested outdoors by Girardin et al. (2016), and because it shows a very similar collection efficiency, particle bounce, and re-aerosolization to the AGI-30 (Grinshpun et al. 1997). Moreover, the AGI-4 was found to be more efficient in collecting submicrometer particles and to be less particle-size dependent than the AGI-30 (Lin et al. 1997).

In this setup, two impingers were fixed on a vertical rod, provided adjustable clamps, and connected to a vacuum pump outside the tunnel. The collectors were tested at a wind velocity of 1 $\mathrm{m\,s^{-1}}$ and air temperatures of 15°C, 25°C, and 35°C. For each temperature, 120 measurement points were considered. The recommended procedure implied at least 30 min of sampling at a 12.5 $\mathrm{L\,min^{-1}}$ suction rate, which is the critical flow for this collector. During this experiment, the AGI-4 air flow was regulated differently from typical applications: a control discharge valve was installed to regulate the intake at approximately 3.7 $\mathrm{L\,min^{-1}}$ (± 0.2 $\mathrm{L\,min^{-1}}$) per impinger to ensure 1 $\mathrm{m\,s^{-1}}$ of local inlet velocity and hence, to meet the isokinetic conditions of the wind velocity of the tunnel and reduce sampling perturbation at the inlet. Airflow was measured using a Copley DFM 2000 flowmeter (Copley Scientific, Nottingham, UK).

A solution of 0.3 $\mathrm{g\,L^{-1}}$ BSF was sprayed at a wind velocity of 1 $\mathrm{m\,s^{-1}}$ and air temperature of 25°C. Similar to the PVC lines, four vertical arrays of horizontal sampling lines were placed downwind at 2, 3.9, 5.8, and 7.7 m from the boom and associated with letters A, B, C, and D, respectively. Each line had five sampling points at 0.7, 1.05, 1.4, 1.75, and 2.1 m from the walls of the wind tunnel. The grid was, therefore, composed of 5 points per ordinate, 30 sampling points per array, and 120 points in total. The sampling time was set to 7 min to limit re-aerosolization, droplet bounce, and liquid losses, typical drawbacks of this sampler.

Setup 3: Droplet-Size Distribution Evaluation Using the Cascade Impactor NanoMoudi 122-NR

There is limited knowledge of the droplet size from sprinklers of less than 1 mm (Li et al. 1994; Montero et al. 2003) and of their evolution subsequent to emission. Moreover, droplet size development is normally investigated near the nozzle outlet using optical devices that ensure no perturbation over the measurement (Stevenin et al. 2016). This method requires sufficient liquid mass for assessment, resulting in a less accurate measurement when farther from the outlet or in highly diluted fluxes, as encountered in irrigation transport quantification. Therefore, alternative nonoptical collectors with much higher mechanical impacts on plume dispersion are necessary. For Setup 3 a NanoMoudi 122-NR cascade impactor (MSP Corporation, Shoreview, Minnesota) was used to assess the particle size distribution (Marple 2004) at a farther distance downwind. The working principle of cascade impactors relies on inertial impaction. When activated, a pressure drop forces air to pass through the device progressively toward reducing perforated plates. During each stage, air is deflected at a 90° angle, causing particles larger than the cut-off size of the stage to cross air streamlines and be captured onto thin aluminum plates, whereas smaller particles with less inertia proceed to the following stage. Air velocity increases following each stage, allowing finer particles to be collected, until their size is so infinitesimal that the device is no longer capable of trapping them. Particles are sorted by aerodynamic diameter. This last parameter corresponds to the diameter of an idealized spherical particle of density 1,000 $\mathrm{kg/m^3}$ with the same aerodynamic behavior as the particle of interest. An analysis of the distribution according to the characteristic diameters D_{vx} (representing the percentage x of the entire volume constituted by particles of less than such a diameter), including D_{v32}, also known as the Sauter diameter, which corresponds to the diameter of a spherical particle with the equivalent volume/surface ratio of the distribution, was conducted.

Setup 3 [Fig. 2(c)] aimed to estimate droplet size using a NanoMoudi 122-NR cascade impactor under fully aerosolized conditions. This device is a 13-stage cascade sampler with a potential range of capture from 10 nm to 18 μm to focus on droplets sufficiently small to not be easily detected using optical sensors. The collector was placed 12 m downwind, and performances were examined at 1, 2, 3, and 5 $\mathrm{m\,s^{-1}}$ at 25°C. The BSF concentration was set to 0.3 $\mathrm{g\,L^{-1}}$. As for AGI-4, the airflow was measured using a Copley DFM 2000 flowmeter. The recorded inlet flow was 30.7 $\mathrm{L\,min^{-1}}$ (± 2.4 $\mathrm{L\,min^{-1}}$) and the sampling time was fixed to 20 min.

Data Processing and Transport Computation

PVC Lines and AGI-4 (Setups 1 and 2)

Given the concentration C_0 of the sprayed solution, the transport was computed as the corresponding quantity of airborne water traveling in the form of fine droplets. Assuming that the amount of water depositing on the sample was negligible compared to the rinsing volume V, the airborne transport T [$\mathrm{L\,h^{-1}\,m^{-2}}$] in Setups 1 and 2 was computed as a flux using the following equation:

$$T = \frac{C_s V}{C_0 \eta A t} \tag{1}$$

where C_0 = fluorescent concentration in the tank (0.13 $\mathrm{g\,L^{-1}}$ for the PVC lines and 0.3 $\mathrm{g\,L^{-1}}$ for AGI-4); C_s = fluorescent concentration found on the samples; V = rinsing volume (20 ml of demineralized water); A = sampling surface (171.4 $\mathrm{cm^2}$ for a PVC line and 0.62 $\mathrm{cm^2}$ for an AGI-4); and t = sampling time (10 s for the PVC lines and 7 min for AGI-4). The collection efficiency η was considered to be 80% for the PVC lines according to low-wind evaluations from Gil and Sinfort (2005). The collection efficiency of AGI-4 was characterized by great variability depending on particle size, airflow, and wind velocity (Willeke et al. 1992; Lin et al. 2000). In Setup 2, the efficiency of AGI-4 was not considered because of insufficient knowledge of AGI-4 capture performance under the investigated air conditions and the droplet range of this study.

The PVC lines were rinsed and reused for each meteorological condition. This caused the lines and the associated sampling equipment to retain a small amount of tracer even subsequent to a thorough rinsing. The background level was determined using 20 random lines (rinsed without any voluntary application of BSF) and the residual transport was assessed as $0.035\ \mathrm{L\,h^{-1}\,m^{-2}}$. This background transport was subtracted from all PVC line measurements obtained using Eq. (1).

Transport values of Setups 1 and 2 are presented in section "Effects of Wind Velocity and Temperature on Airborne Transport" as vertical profiles. For every temperature and wind velocity, all sets of profiles were normalized with the highest transport value retrieved from each experiment.

In Setup 1, two complementary functions Z_m and T_m were introduced to evaluate the behavior of the plume referring to its center of mass. The function (m) individuates the transport-averaged height of each profile and it is addressed to draw the trajectory of the plume. The function T_m $(\mathrm{L\,h^{-1}\,m^{-2}})$ represents the mean transport of each profile, with the assumption that transport linearly evolves from an ordinate to another. These functions were calculated as follows:

$$Z_m = \frac{\sum_{i=1}^{7} z_i T_i}{\sum_{i=1}^{7} T_i} \tag{2}$$

$$T_m = \frac{1}{2(z_7 - z_0)} \sum_{i=1}^{7} (T_i + T_{i-1})(z_i - z_{i-1}) \tag{3}$$

where z_i = height from the ground; and T_i = associated transport value. $i = 0$ corresponds to ground level where transport is assumed to be zero.

In Setup 2, the sampling grid was characterized by five acquisition points per ordinate and local airborne transport T_j was still computed using Eq. (1). To compare the results from the AGI-4 to those from the PVC lines, the AGI data were averaged through the transversal axis of the wind tunnel. Similar to Eq. (3), two assumptions were made as follows: (1) local transport at the borders of the tunnel was equivalent to zero and (2) transport linearly evolved from one acquisition point to the other and from the borders of the tunnel.

Considering $j = 0$ and $j = 6$ as the side walls of the wind tunnel, and $j = 1, 2, 3, 4$, and 5 as the five local acquisition points, the averaged transport $\bar{T}$ $(\mathrm{ml\,h^{-1}\,m^{-2}})$ for each ordinate was thus calculated using the following:

$$\bar{T} = \frac{1}{2(l_6 - l_0)} \sum_{j=1}^{6} (T_j + T_{j-1})(l_j - l_{j-1}) \tag{4}$$

where l_j = distance of acquisition from the side wall; and T_j = local transport. The results are presented in the next section both in normalized and absolute values.

Multistage Impactor (Setup 3)

In Setup 3, the water volume D deposited on the impaction plates in the cascade impactor was given by the following:

$$D = \frac{C_s V}{C_0} \tag{5}$$

where C_0 = fluorescent concentration in the tank $(0.3\ \mathrm{g\,L^{-1}})$; C_s = concentration found on each plate; and V = rinsing volume (5 ml of demineralized water).

The sharpness, σ, of the droplet-size distribution in Setup 3 was calculated as follows:

$$\sigma = \sqrt{\frac{D_{v85}}{D_{v15}}} \tag{6}$$

where D_{v85} and D_{v15} = diameters corresponding to 85% and 15% of the collected volume, respectively.

Results

Effects of Wind Velocity and Temperature on Airborne Transport

Sampled Volume

A shown in Fig. 3, the volume of water collected on the PVC lines is expressed as a percentage of the sprayed volume. The total volume collected by PVC lines does not exceed 4% of the sprayed volume. This confirms that such a technique does not disturb the spray. The figure shows that the collected fraction increases with wind velocity and, as expected, it is not notably affected by temperature in such a saturated condition.

Evaluation of Transport

Transport was calculated using Eq. (1) and is presented in the form of vertical profiles as shown in Fig. 4. The results of each of the nine air conditions were normalized by the maximum transport value obtained for Set A (listed in Table 1, Set A). Normalized transport profiles for different wind velocities were sorted by temperature. Wind velocity demonstrates a relevant effect on the plume shape. In particular, it affects the elevation of the local peak and extends the permanently airborne condition of the plume. The local peak intensity denotes a decrease, from Set A to Set D, of approximately 87% at $1\ \mathrm{m\,s^{-1}}$, 74% at $2\ \mathrm{m\,s^{-1}}$, and 62% at $3\ \mathrm{m\,s^{-1}}$. Thus, deposition decreases as wind velocity increases.

Scarcity or even absence of deposition is observed on the upper lines (typically greater than 1.5 m). This probably can be attributed to the presence of very few droplets at this height, the limited collection efficiency of PVC lines for very small droplets, and the presence of a residual transport value (i.e., $0.035\ \mathrm{L\,h^{-1}\,m^{-2}}$) in

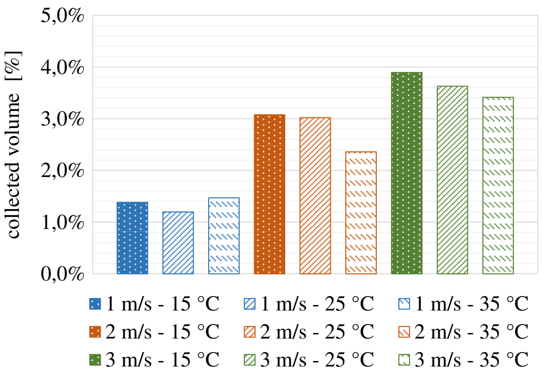


Fig. 3. Volume of water collected on the PVC lines (Setup 1) as a percentage of the initial sprayed volume (Setup 1).

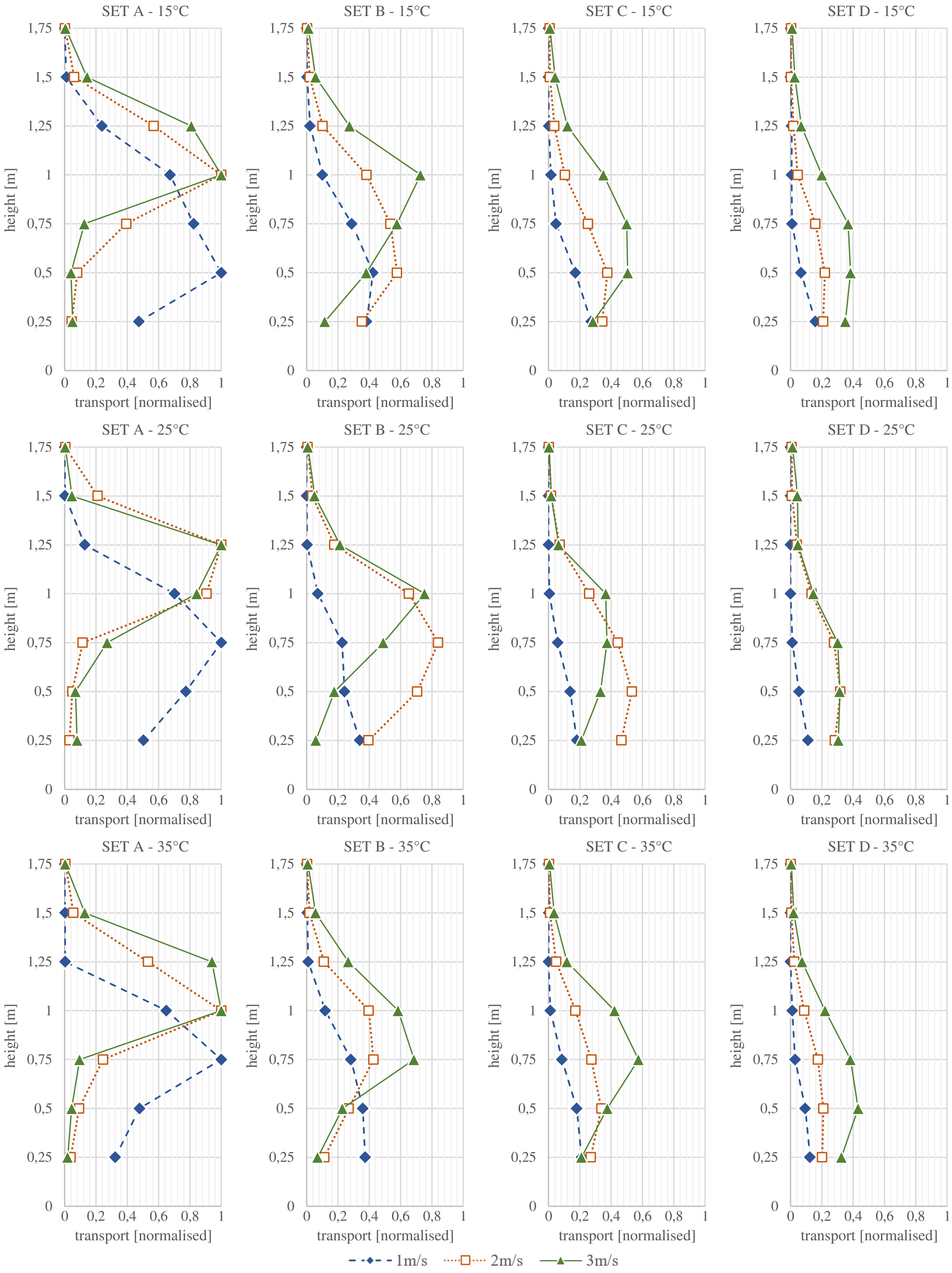


Fig. 4. Normalized airborne transport profiles for different wind velocities and temperatures, evaluated using PVC lines (Setup 1).

the lines and the associated sampling equipment. Below this threshold, it is not possible to determine whether the line is effectively marked with dye.

Table 2 introduces collection data as influenced by the wind velocity and temperature in terms of mean value and variation coefficient, as provided by the ratio between the standard deviation and its mean value. As expected, wind velocity effects were more important than those accredited to temperature under such saturated conditions. Transport values were sorted by wind velocity and by temperature. The variation attributed to wind velocity is mostly greater than 40% (COV for temperature lines) and that because of temperature is generally limited between 10% and 20% (COV for wind velocity lines). Because evaporation is considerably restrained, the effects of wind velocity are predominant and temperature evidently plays a minor role when approaching saturation conditions.

Table 1. Intensity of the local peaks of airborne transport in Setup 1 using the PVC lines for each temperature and wind condition tested

Wind velocity ($\mathrm{m\,s^{-1}}$)	Temperature (°C)	Local peak value ($\mathrm{L\,h^{-1}\,m^{-2}}$) Set A[a]	Set B	Set C	Set D
1	15	4.05	1.71	1.10	0.64
	25	4.00	1.36	0.72	0.44
	35	4.10	1.53	0.86	0.50
2	15	6.33	3.38	2.37	1.38
	25	4.16	3.86	2.44	1.46
	35	5.60	2.38	1.88	1.17
3	15	6.28	4.57	3.17	2.40
	25	6.68	5.03	2.49	2.10
	35	5.66	3.88	3.25	2.44

[a] Local peak values of Set A are identified as the maximum transport values ever encountered in this experiment.

Table 2. Mean value and coefficient of variation of transport for Setup 1 using the PVC lines

Common parameter	Set A Average	Set A COV	Set B Average	Set B COV	Set C Average	Set C COV	Set D Average	Set D COV
1 $\mathrm{m\,s^{-1}}$	1.67	12.98	0.63	17.09	0.26	15.27	0.13	19.86
2 $\mathrm{m\,s^{-1}}$	1.67	13.84	1.56	27.72	1.02	13.95	0.61	11.73
3 $\mathrm{m\,s^{-1}}$	1.98	10.26	1.70	11.48	1.44	11.35	1.18	6.25
15°C	1.91	2.41	1.46	45.19	0.97	68.02	0.66	84.30
25°C	1.81	19.47	1.34	54.36	0.89	65.83	0.63	79.70
35°C	1.60	11.51	1.09	39.71	0.86	65.40	0.63	82.41

Note: The variation coefficient (COV) is introduced as an indicator of the effect of wind velocity or temperature on airborne transport. When local peaks of transport are averaged and sorted by wind velocity, COV expresses the effects of temperature; when sorted by temperature, COV expresses the effects of wind velocity; Average = arithmetic mean of the local peaks ($\mathrm{L\,h^{-1}\,m^{-2}}$); and COV = variation coefficient (%).

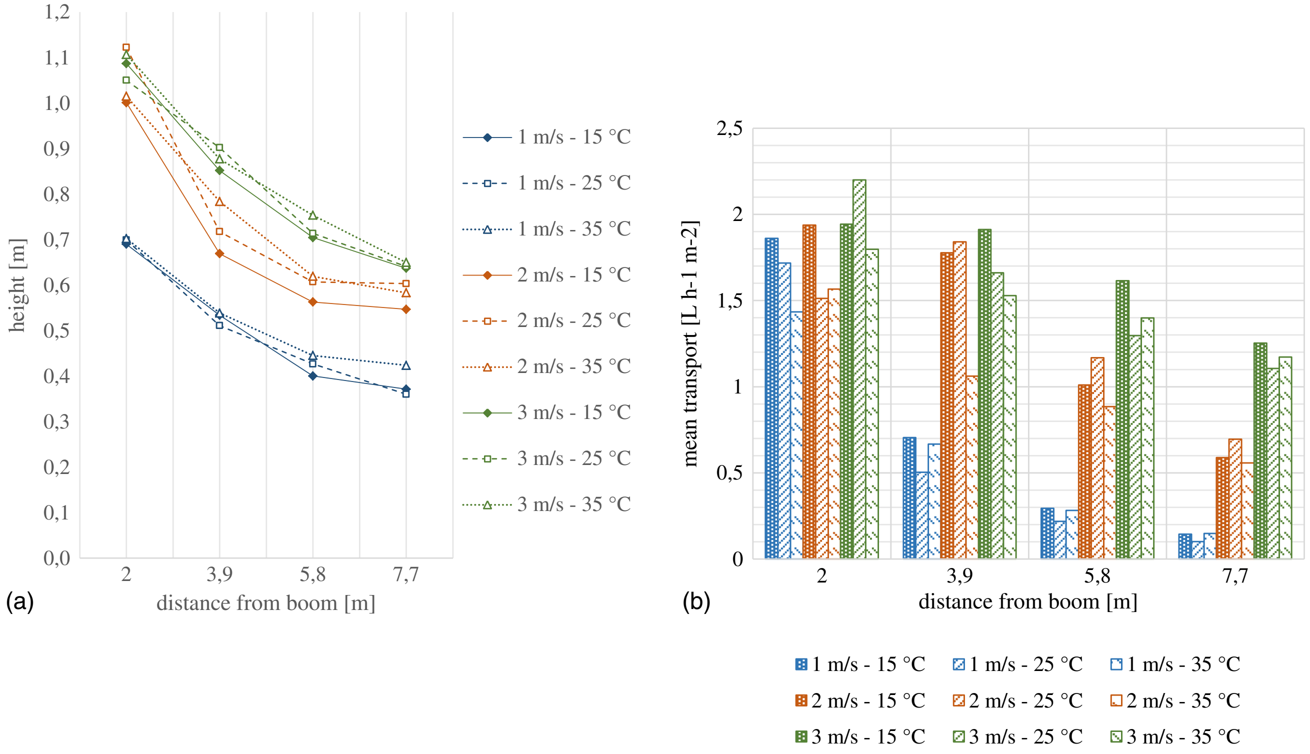
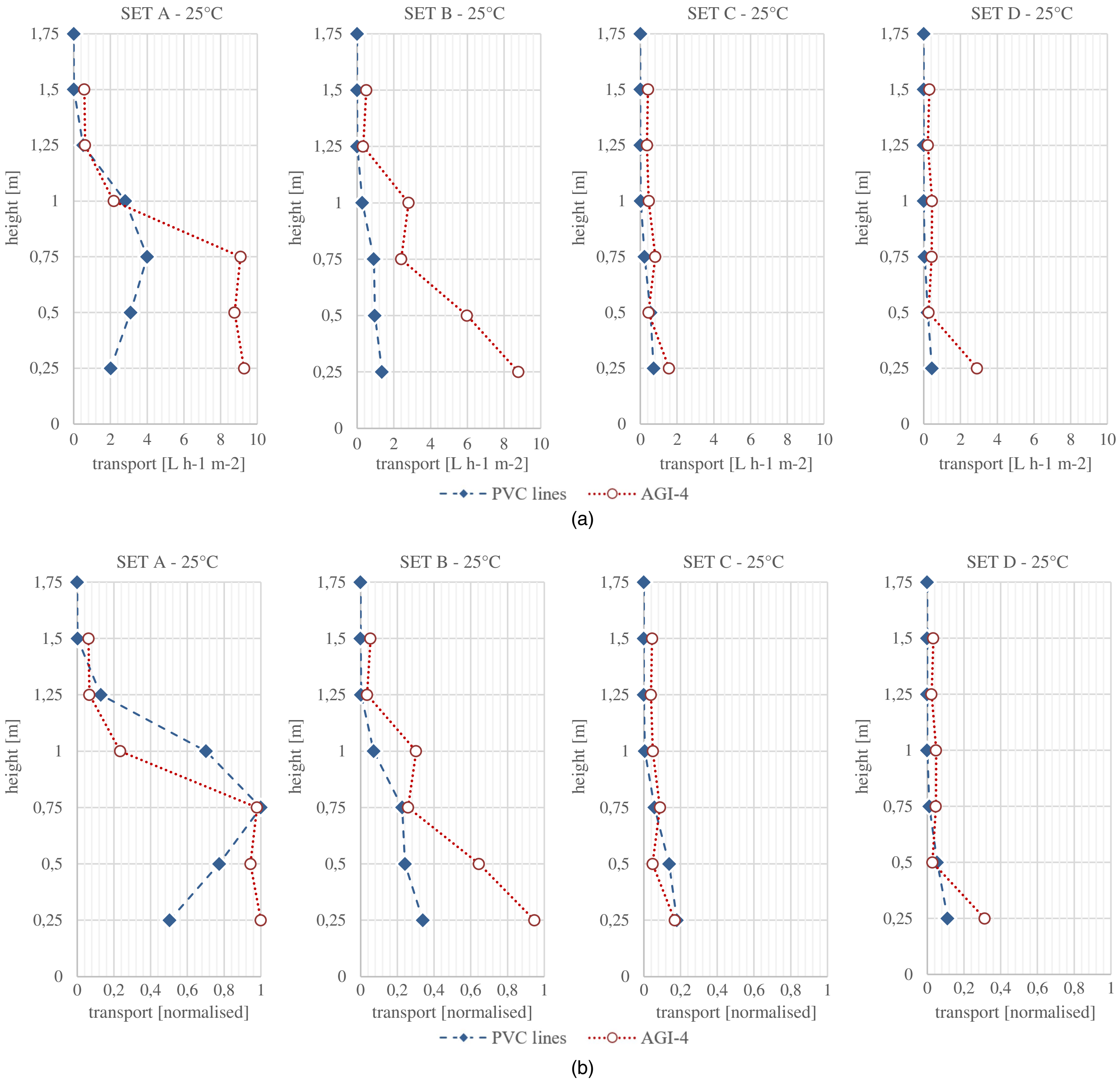


Fig. 5. (a) Downwind trajectories of the plume center of mass for the different air conditions in Setup 1; and (b) downwind evolution of total transport for every set of PVC lines for the different air conditions in Setup 1.



(a)

(b)

Fig. 6. Comparisons of (a) absolute transport profiles between the active collector AGI-4 (Setup 2) and passive PVC lines (Setup 1); and (b) normalized transport profiles between active collector AGI-4 (Setup 2) and passive PVC lines (Setup 1).

Plume Trajectory

The trajectories of the center of mass, obtained using Eq. (2), are plotted in Fig. 5(a). For each wind velocity, the three curves (for different temperatures) are nearly superimposed; these results also confirm the minor effect of the temperature on transport at saturation. The center of mass is relocated on higher ordinates as wind velocity increases. A stronger wind velocity causes a shift upward of the center of mass, allowing the spray to last longer airborne and travel farther. Additionally, the increase in wind velocity also leads the airborne plume to maintain a more compact form and carry a higher volume of water. This last aspect is shown in Fig. 5(b), which represents the downwind evolution of mean transport, computed using Eq. (3), for various air conditions. Mean transport decreases as the distance from the spray generator increases (from Set A to Set D) by approximately 92%, 63%, and 40%, respectively, at 1, 2, and 3 $\mathrm{m\,s^{-1}}$.

Transport Recovery Efficiency: Comparison between AGI-4 and PVC Lines

Airborne transport was assessed using AGI-4 samplers according to a sampling grid of 120 points. Only averaged values (five values per height) are shown in Fig. 6(a): transport was locally evaluated using Eq. (1) and then estimated using Eq. (4), to compare the results to PVC lines. The total volume collected by the impingers was 2.93% of the sprayed volume, approximately twice that collected by the

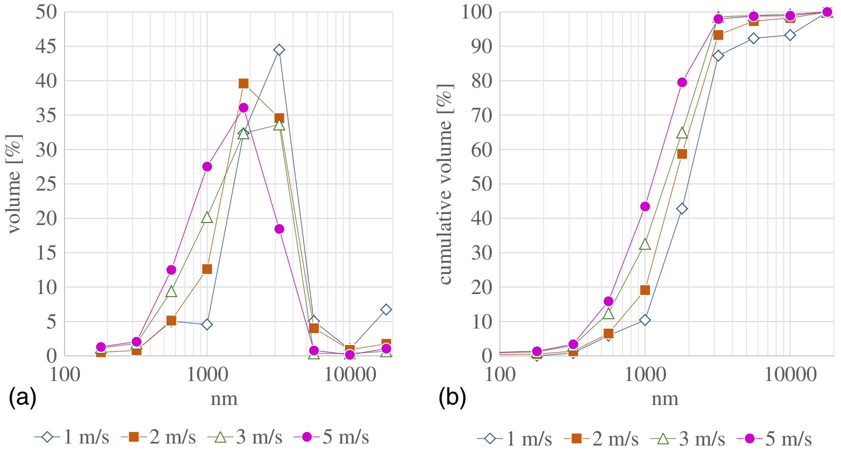


Fig. 7. (a) Droplet-size distributions estimated using the cascade impactor (Setup 3) for increasing wind velocities 12 m from the boom; and (b) cumulative droplet-size distributions estimated using the cascade impactor (Setup 3) for increasing wind velocities 12 m from the boom.

PVC lines under analogous conditions, considering that the available sampling surface of the employed AGI-4 was only 1.54% that of PVC lines.

The AGI-4 profiles shown in Fig. 6(b) show a similar "belly" shape as that of the PVC lines in terms of normalized recovery, demonstrating that this type of sampler can also be also used for quantification. The highest value of averaged transport of AGI-4 is 9.28 $\mathrm{L\,h^{-1}\,m^{-2}}$ (for Set A at 0.25 m). This was used to normalize the AGI-4 profiles as shown in Fig. 6(b). However, as a general feature, the impingers recovered much higher quantities, up to a factor of 9 (i.e., for Set B at 0.25 m) compared to those of the PVC lines [Fig. 6(a)]. When high-intensity transport was encountered, generally for sampling heights of less than 0.5 m, AGI-4 exceeded the PVC lines at least by a factor between 2.2 and 3. However, for Sets C and D, AGI-4 retrieved few traces of dye, thus proving their better sensitivity compared to that of the PVC lines in low-intensity transport (less than 1 $\mathrm{L\,h^{-1}\,m^{-2}}$).

Droplet-Size Distribution

The NanoMoudi 122-NR impactor consists of 13 sampling plates. During this analysis, the last three stages were not included in the results because only negligible traces of fluorescence were observed, which were below the reliability threshold of the device. Droplet-size distribution was thus examined within the range of from 100 nm to 18 μm. Collected volume was calculated using Eq. (5). As shown in Figs. 7(a and b), the droplet-size distribution appears reasonably uniform and of the same order of magnitude in the investigated range of wind velocities. As shown in Table 3, the median volume diameter Dv_{50} decreases from 1 to 5 $\mathrm{m\,s^{-1}}$ by a factor 1.77. This decrease is higher for Dv_{15}, which is nearly halved by a factor 2.05, whilst Dv_{90} is less affected and reduced by a factor of 1.41. The increase in wind velocity causes the translation of the distribution toward smaller diameters, a slight enlargement of the distribution width, and a small increase in the sharpness but a decrease in peak value, as shown in Fig. 7 and Table 4. The shift is more evident in the cumulative distribution as shown in Fig. 7(b).

The deposited droplet volume rapidly decreases in an exponential trend as can be seen in Fig. 8; the collected volume of water decreases by 71% from 1 to 2 $\mathrm{m\,s^{-1}}$ and by 95% from 1 to 5 $\mathrm{m\,s^{-1}}$. Despite that there may have been an actual variation in size, the relevant reduction in the deposit rather suggested a decrease in device capture efficiency. Upton et al. (1994) observed analogous behaviors using a multistage Andersen impactor. Most likely, the increase in wind causes heavier droplets, with greater inertia, that are less affected by the inlet flow of the cascade impactor and their trajectories are not altered such to enter the collector. Therefore, droplet-size distribution slightly flattens and shifts to smaller diameters. Given the similarity in size distribution for all velocities, the wind velocity already affects negatively airborne recovery at 2 $\mathrm{m\,s^{-1}}$.

Time of Flight

It has been previously shown that the transport values collected on the PVC lines show dependence on the sampling distance and wind velocity. It is then possible to merge these two setting parameters in a single parameter expressed as a time period, that is, the ratio between the sampling distance and the wind velocity (x/U). Because this transport time corresponds to the traveling time for droplets before collection by the samplers, this time is termed *time of flight* (ToF). The dependence of the transport on the time of flight, despite not being really studied as such in the literature, is a practical and

Table 3. Droplet-size distribution as measured using the cascade impactor (Setup 3) under fully aerosolized conditions 12 m from the boom

Volume distribution	Wind velocity ($\mathrm{m\,s^{-1}}$) 1	2	3	5
	Aerodynamic diameter (nm)			
Dv_{10}	960	682	626	447
Dv_{15}	1,113	856	617	543
Dv_{32}	1,534	1,260	987	817
Dv_{50}	2,027	1,624	1,430	1,145
Dv_{85}	3,128	2,863	2,634	2,216
Dv_{90}	4,493	2,330	2,842	2,595

Table 4. Droplet-size distribution sharpness as measured using the cascade impactor (Setup 3) under fully aerosolized conditions 12 m from the boom

Wind velocity ($\mathrm{m\,s^{-1}}$)	Distribution sharpness
1	1.68
2	1.83
3	2.87
5	2.02

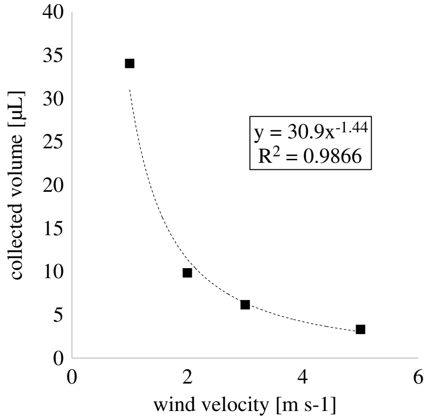


Fig. 8. Rapid decrease in the collected volume of aerosols in the cascade impactor (Setup 3) with an increase in wind velocity.

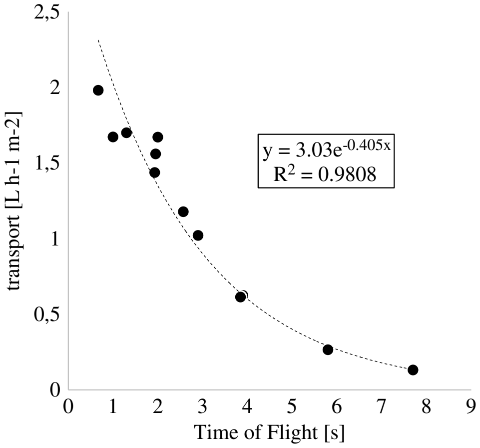


Fig. 9. Evaluation of the time of flight for every value of airborne transport found on the PVC lines (Setup 1).

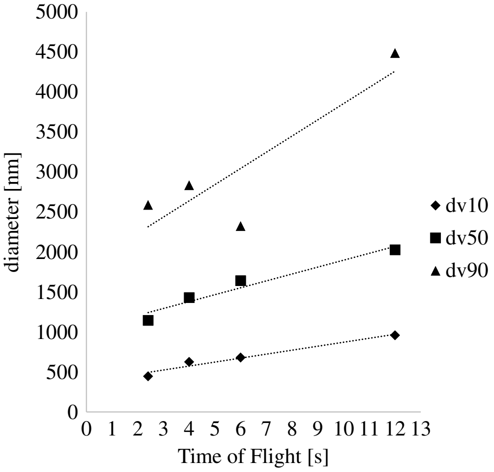


Fig. 10. Correlation between the time of flight and the aerodynamic diameter of every droplet-size distribution from Setup 3. Heavier particles are more likely to be affected by the rate of change in the wind velocity; therefore, their time of flight is more consistently reduced with an increase in wind velocity.

measurable consequence of the transport equation. A Gaussian advection-diffusion model described by Lebeau et al. (2009) indeed includes an x/U term, which was analyzed in this study through the ToF.

As shown Fig. 9, considering any distance of collection, ToF notably decreases along with the relevant intensification of transport as wind velocity increases, most likely with an exponential trend. Although the coefficient of determination indicates a good fit of the exponential model to the point distribution, more specific studies should be proposed to explore different meteorological conditions and spray generators and thus generalize such an empirical model.

Fig. 10 shows the ToF for Setup 3, where the distance was fixed at 12 m. One can observe that relatively heavier droplets tend to be more affected by wind velocity. Droplet-size distribution tends to contract as the wind velocity increases, resulting in a ToF reduction. This occurrence agrees with Setups 1 and 2 because the plume tends to stay more compact and concentrated as the wind increases, resulting in heavier droplets to delay deposition more so than lighter droplets.

Conclusion

This study aimed to quantify temperature and wind effects on transport that may occur during sprinkler irrigation. It re-elaborated existing sampling methods from other fields of interest to characterize the spray evolution and evaluate the sampling efficacy of different types of collectors, in view of sprinkler irrigation using TWW.

Results show that PVC lines are reliable collectors to describe the evolution of the spray plume within a short range because they withstand high-intensity transport without excessive disturbance of the droplet flux. The increase in the wind velocity extensively prolongs the permanently airborne condition of the plume as a more compact and concentrated flux occurs. As expected, temperature variations (from 15°C to 35°C) have negligible effects on transport under saturated conditions, denoted by the lesser variance as compared to wind velocity. The effects of temperature could be better appreciated when operating far from saturation conditions that impede strong evaporation and with a more extended workbench. In this study, the PVC lines could not characterize fine transport at less than 0.35 $\mathrm{L\,h^{-1}\,m^{-2}}$. This is likely attributed to the limited capability to intercept very small droplets, the presence of a background value in the sampling equipment, and the very limited sampling time that did not allow for a significant BSF deposit. This suggests that PVC lines might not be sufficient to detect low-intensity transport that could occur far from an emission point but, in contrast, they better characterize at a closer proximity.

PVC lines and AGI-4 show some similarities but also relevant differences in recovery. Transport values from AGI-4 are relevantly higher, ranging from a factor of 2.2–3 up to 9. This difference is greater where the transport is more intense. Nevertheless, AGI-4 appears more suitable to assess low transport (since it was originally conceived to sample pathogens and for longer exposures) because it shows greater sensitivity than that of the PVC lines, as in the samples less than 1 $\mathrm{L\,h^{-1}\,m^{-2}}$. The sampling mechanism probably plays a more important role than that of the sampling surface extension: the total volume collected by the AGI-4 is 2.93% of the sprayed volume, approximately twice that collected by the PVC, with a sampling surface only 1.54% that of the PVC lines. A specific investigation is recommended to evaluate AGI-4 adaptability to air flow modification under windy conditions.

The droplet-size distribution from 0.1 to 18 μm was investigated. Droplet-size distributions were similar within the whole range of wind velocity, but the increase in velocity causes the distribution to flatten and shift toward smaller diameters. Moreover, the overall collected volume exponentially decreases with an increase in wind velocity, demonstrating the inability of the device to withstand windy conditions. Given these results, the use of such mechanical devices for field sampling is discouraged in favor of optical ones.

A new parameter, the time of flight, was proposed with the intent of its inclusion within the decision tools to secure policies and practices for irrigation with TWW because it might represent an intuitive indicator to assess dangerous conditions and to advise safe distances during application. However, observations should be extended to a wider set of droplets, meteorological conditions, and irrigation devices on the fields.

This study provides a basis for the development of a robust protocol to characterize airborne transport for sprinkler irrigation using TWW. It is a preliminary approach that could be included in decision tools or used to secure policies and practices. Studies are needed to analyze how droplet-size distribution spatially evolves as wind velocity, temperature, and humidity vary, and for different sprinkler types. In addition, the next steps should include planned experiments using particles more representative of pathogens (e.g., microspheres and virus-like particles). This could help validate assumptions for plume boundaries and explain differences in the effectiveness among collection devices.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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