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Evaluating the distribution uniformity of ten overhead sprinkler models used in container nurseries

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Abstract

Nurseries and greenhouses face challenges of limited water supply and increased demand for irrigation efficiency to minimize runoff and mitigate water loss to the environment. Overhead irrigation systems are among the most widely used methods for container plants, particularly in small container sizes. However, there is a lack of research examining the distribution uniformity (DU) of the most used sprinklers in nursery settings. Our study investigated the DU of different overhead sprinkler types and models commonly used in outdoor nurseries in the United States to guide greater adoption of higher irrigation efficiency technology. Catch-can experiments compared ten different sprinkler models in small (4.6 m x 4.6 m) and large (9.1 m x 9.1 m) square experimental plots in Irvine, California. We measured water volume, wind speed, and operating pressure, and calculated the application rate for 189 test runs conducted between Mar 2020 and May 2023. Our results show that of the models tested, the greatest DU was achieved by the Hunter MP2000 at 276 kPa (DU = 0.78 ± 0.05) in the small spacing, and the Senninger Xcel

Wobbler with a 3.97 mm nozzle at 172 kPa (DU = 0.76 ± 0.06) in the large spacing. Wind speed and operating conditions affected the DU and spatial uniformity of irrigation among the ten models, highlighting the importance of maintaining operating pressures at the manufacturer's recommendations to ensure optimal application rates and DU. Together these results offer a quantitative comparison of sprinkler performance at different operating pressure and in a wide range of wind speeds, allowing users to select sprinkler models that best fit their operation and maximize water conservation.

Keywords: overhead sprinklers, distribution uniformity, nurseries, wind speed, application rate, operating pressure.

Highlights:

- Compared distribution uniformity (DU) of impact, geared rotor, wobbling sprinklers
- Hunter MP2000, Senninger Xcel wobbler had the highest DU at lowest operating pressure
- DU of most sprinklers was significantly negatively correlated with wind speed
- Small test plot size created artifacts in relationship between DU and application rate

1 Introduction

In response to global declines in surface and groundwater supplies, container-grown plant production, especially in nurseries, is increasingly being asked to cut water use by improving irrigation efficiency (Pershey, 2014; Pershey et al., 2015; Wang et al., 2015). Water conservation and water quality impacts of nursery runoff on ecosystems have particularly come to the forefront of nursery management as many regions experience more frequent droughts and customers become more environmentally conscious. To address these growing environmental and socio-economic pressures, production nurseries have adopted new water management best practices that reduce runoff, sediment, and nutrient losses to not only meet growing regulatory demands but to also improve overall productivity, crop health, plant growth, and profitability. For container-grown plant production and landscape irrigation applications, overhead sprinkler systems are still very popular because of their practicality and ease of use (Beeson and Knox, 1991), as they are less labor intensive compared to drip, particularly in small container sizes. Despite being inherently less efficient than localized irrigation systems, sprinkler systems can be designed and managed to effectively mitigate water loss by maximizing coverage, reducing evaporation, minimizing runoff, and controlling wind drift. However, there exist several different overhead sprinkler types that vary in operating pressure, application rate, distribution uniformity, and irrigation efficiency that nursery managers can choose from. To maximize water conservation in nurseries, it is important to assess and compare the irrigation efficiency of existing sprinkler systems to guide nursery managers in their decision-making process.

Both the irrigation efficiency (defined as the ratio of total water amount applied and water amount needed to meet crop demand or other beneficial uses) and distribution uniformity (DU; indicator of how evenly water is applied to crops in an irrigated area) of a sprinkler system vary depending on sprinkler type and operating conditions (Burt et al., 1997; Darko et al., 2017; Tarjuelo et al., 1999). Common overhead sprinkler types currently used in nurseries and landscape irrigation include widely different technologies and configurations: (i) *Multi-Stream Multi-Trajectory* (MSMT) nozzles, which emit multiple streams of water for comprehensive coverage; (ii) *geared rotor* sprinkler heads, utilizing rotating gears to adjust water distribution in a circular pattern; (iii) *impact* sprinkler heads, delivering water in a pulsatile manner via a swinging arm mechanism for extensive coverage; and (iv) *wobbling* sprinkler heads, spinning and oscillating to deliver uniform water distribution. While some sprinkler technologies like impact, and geared rotor sprinklers are able to irrigate larger areas, newer sprinkler technologies such as “wobbler,” or Multi Stream Multi Trajectory (MSMT) sprinkler heads are recognized for delivering higher uniformities and efficiency (Li et al., 2022; Solomon et al., 2007).

Operating conditions, such as wind speed, operating pressure, spacing between sprinklers, and sprinkler spatial layout, have consistently emerged as key factors in maximizing DU in sprinkler irrigation systems. High wind speeds (>4 m/s) are widely recognized as detrimental to achieving high DU, as demonstrated by the repeated negative correlations observed between wind speed and DU (Boja et al., 2012; Dehkordi et al., 2016; Demirel and Sener, 2009; Kumar et al., 2023; West, 2014). There is conflicting evidence on whether operating pressure, which influences the flow rate, the application rate, and the spray radius, improves, or reduces irrigation uniformity across sprinkler types. The optimal performance of irrigation systems relies on their operating pressure, which influences the flow rate, the application rate, and the spray radius. Pressures outside the range recommended by manufacturers can result in poor distribution (Zhang et al. 2013) and loss of water. Higher than manufacturer-recommended operating pressures can generate smaller droplets (misting) that may be more prone to losses due to evaporation and wind drift (Li 1997, Montero et al. 2003) and greater flow volumes exiting the sprinkler head (Tarjuelo et al. 1999a), which can increase water application and energy cost (Montero et al. 2004, Sheikhesmaeili et al. 2016). On the other hand, low operating pressures are known to produce a doughnut or ring-shaped pattern (Christiansen 1942, Zhang 2018) due to decreasing water distribution close to the sprinkler head. In general, DU is highest if the sprinkler is operated within the recommended pressure range and decreases when the pressure falls below this range.(Abd El-Wahed et al., 2016; Montazar and Moridnejad, 2008; Tarjuelo et al., 1999, Dehkordi et al., 2016). Besides operating pressure, optimal sprinkler spacing relative to throw diameter (i.e. the diameter of the circular area wetted by the sprinkler), and layout geometry are shown to be crucial to achieving high uniformity. Previous studies have also shown that the larger the spacing between sprinklers, the lower is the irrigation uniformity, which can be further exacerbated by high wind speeds (Tarjuelo et al. 1999b). As a result of these studies, Amer (2006), for example, recommends a spacing of 50% to 60% of the sprinkler's throw diameter for impact and spinner sprinklers assuming a square layout, while Khedr (2020) suggests 50-70% spacing for square layouts for impact sprinklers. In contrast, Keller and Bliesner (1990), Amer (2006) and Elhussiny et al. (2023) suggest triangular layouts may offer greater uniformity under similar tested conditions.

To date only a few papers have specifically examined the DU of sprinkler irrigation in outdoor nursery settings. Million and Yeager (2015) and Beeson and Knox (1991) examined factors affecting the irrigation efficiency of potted plants in outdoor nurseries, but not specifically the DU of the sprinkler systems. Most studies that compare sprinkler types or models from different manufacturers have focused on two, but rarely more than three types (Demirel and Sener, 2009; Solomon et al., 2007; West, 2014). Thus, if nursery managers wanted to compare the distribution uniformity and/or irrigation efficiency of a range of sprinkler systems for their operation, multiple studies under different conditions would need to be reviewed. Additionally, no studies were identified for the following sprinkler models included in this study: MSMT (K-Rain RN200, RainBird R-VAN 18-360, Toro PRN-F, Hunter MP3000-360), Rotary (Nelson R2000LP-plate), and Impact (Rainbird LF2400). This study compared the performance of a range of sprinkler types (impact, rotary, wobbler, and MSMT) in a single nursery setting to help fill this gap and provide insight into sprinkler distribution uniformity.

The objective of this study is to assess the distribution uniformity (DU) and irrigation efficiency of different sprinkler types and models commonly used in nurseries in the United States. By examining varying types and models, including impact, rotary, wobbler, and MSMT sprinklers in the same test setting, the study seeks to provide insights into sprinkler performance under different outdoor conditions (e.g. wind speed, operating pressure). Through outdoor catch-can container experiments, this study aims to improve understanding of the relationship between performance parameters and uniformity to guide decision-making for nursery managers.

2 Materials and Methods

2.1 Study site and experimental design

The study was conducted at the University of California Division of Agriculture and Natural Resources South Coast Research and Extension Center (SCREC). SCREC is an 81-hectare (200-acre) outdoor research facility located at 126 m elevation above sea level in Irvine, California, approximately 17 km (10 miles) northwest of the Pacific coastline. The facility has a maritime Mediterranean climate with a mean annual precipitation of 365 mm (14.37 in), primarily occurring during the winter months, and westward prevailing winds. The mean maximum summer temperature (July-August) at the site is 28°C (83°F), and the mean minimum winter temperature (December-January) is 8°C (47°F).

Ten different sprinkler models were tested using catch-can experiments within a 30.5 m x 61 m (approximately 100 ft x 200 ft) gravel bed area at SCREC. These catch-can experiments were conducted using two different sprinkler spacings: (i) 9.1 m x 9.1 m (30 ft x 30 ft) (referred to as large spacing) and (ii) 4.6 m x 4.6 m (15 ft x 15 ft) (referred to as small spacing). These spacings were chosen based on typical nursery plot layouts found at commercial nurseries in southern California. Additionally, the spacings were chosen based on the availability of commercial irrigation sprinkler heads. The spacings chosen are appropriate for the radii of each group of sprinklers selected. Depending on the sprinkler spacing, the arrangement of the catch-can experimental plots changed, as illustrated in Figure 1. For the 9.1 m x 9.1 m sprinkler spacing, the two square experimental plots were spaced 21 m (69 ft) apart, while for the 4.6 m x 4.6 m sprinkler spacing, the two plots were spaced 25.6 m (84 ft) apart. At each plot the sprinkler heads were mounted at the four corners of the plot on 61 cm tall (24 in) and 1.9 cm (0.75 in) diameter risers. With additional fittings, the actual sprinkler height above the ground was 76.2 cm (30 in). Additionally, each sprinkler was connected to a pressure regulator to maintain a uniform and optimal pressure as detailed in Table 1. The use of different regulators may have resulted in slight variations in the final height of each sprinkler model. The sprinklers were fed by a 5.1 cm (2 in) PVC submain that reduced to 2.5 cm (1 in) at the main valve and to 1.9 cm (3/4 in) laterals that served the sprinkler heads. The 5.1 cm submain connected to municipal water supplied by a buried PVC mainline located southeast of the experimental area.

A total of 36 catch-cans, each measuring 19.05 cm (7.5 in) in height and 17.78 cm (7 in) in diameter, were evenly distributed in six rows and six columns within the plots. Catch-cans located along the perimeter of the plot were positioned 15.24 cm (6 in) from the perimeter. The spacing between the catch-cans was 1.77 m (69.7 in) for the large spacing and 0.85m (33.6 in) for the small spacing. Additionally, a 3-cup MetONE anemometer (Model 014A-L, Campbell Scientific Inc., Logan, UT, USA) was placed between the two experimental plots to measure wind speed. For the large spacing experiments, it was centered between the plots, approximately 10.5 m (34.5 ft.) from each plot. For the small spacing, it was positioned off-center at 10.5 m from the left plot and 15.1 m (49.5 ft) from the right plot. The anemometer was installed at a standard height of 2 m (6.56 ft) above ground to facilitate comparison with wind speed measurements provided by a nearby weather stations managed by the California Irrigation Management Information System (https://cimis.water.ca.gov/). For comparison, hourly wind speed and wind direction data were used from CIMIS station #75 Irvine.

Ten different sprinkler models, representing the four sprinkler types introduced above (e.g. Multi-Stream Multi-Trajectory (MSMT) nozzles, geared rotor nozzles, impact nozzles, and wobbling nozzles) were tested in this study. Six of these models (Hunter MP-3000-360, Nelson R2000LP, Rainbird 5000Plus, Rainbird LF2400, Rainbird 2045PJ, and XCEL-Wobblers HA), representing the four types of sprinklers, were tested at the larger spacing (9.1 m x 9.1 m) between March and July of 2022. The remaining four models (Hunter MP-2000-360, K-rain RN200, Rainbird R-VAN18-360, and Toro PRN-F), all MSMT-type nozzles, were tested in the smaller spacing (4.6 m x 4.6 m) between September 2022 and May 2023. Specifications of the tested sprinkler models are provided in Table 1. The sprinkler models were chosen a) to test a wide range of sprinkler technologies; b) because they are sprinklers manufactured by established and reputable brands; and c) commercially available through distributors for purchase to growers. Impact sprinklers emit a water jet that hits the sprinkler's rotary arm, causing it to rotate and scatter the water within the circle of rotation. The arm then moves back to its original position, where it hits the water stream again and repeats the cycle. Gear drive sprinklers (e.g. Rainbird 5000) have a “keyhole” shaped nozzle on a fully rotating head that rotates 360° with the energy imparted by the water pressure and the irrigation stream is not regularly interrupted by a spoon like in the case of impact sprinklers. Nelson Rotators (e.g. Nelson R2000) are similar to gear drive sprinklers, but the nozzle sprays water vertically, and a “plate” deflects the water jet horizontally and breaks the stream with a diffuser. Rotators also have a “flow control” nozzle that contracts under high pressure. Wobbling nozzles (e.g. Senninger Wobblers) spray the water vertically, instead of horizontally at an angle like traditional impact sprinklers, and a deflector rotating on one axis and oscillating on another (wobbling) breaks the stream and directs the water horizontally away from the sprinkler. Multi-stream multi-trajectory nozzles, divide water in single streams that constantly rotate assuming different trajectories.

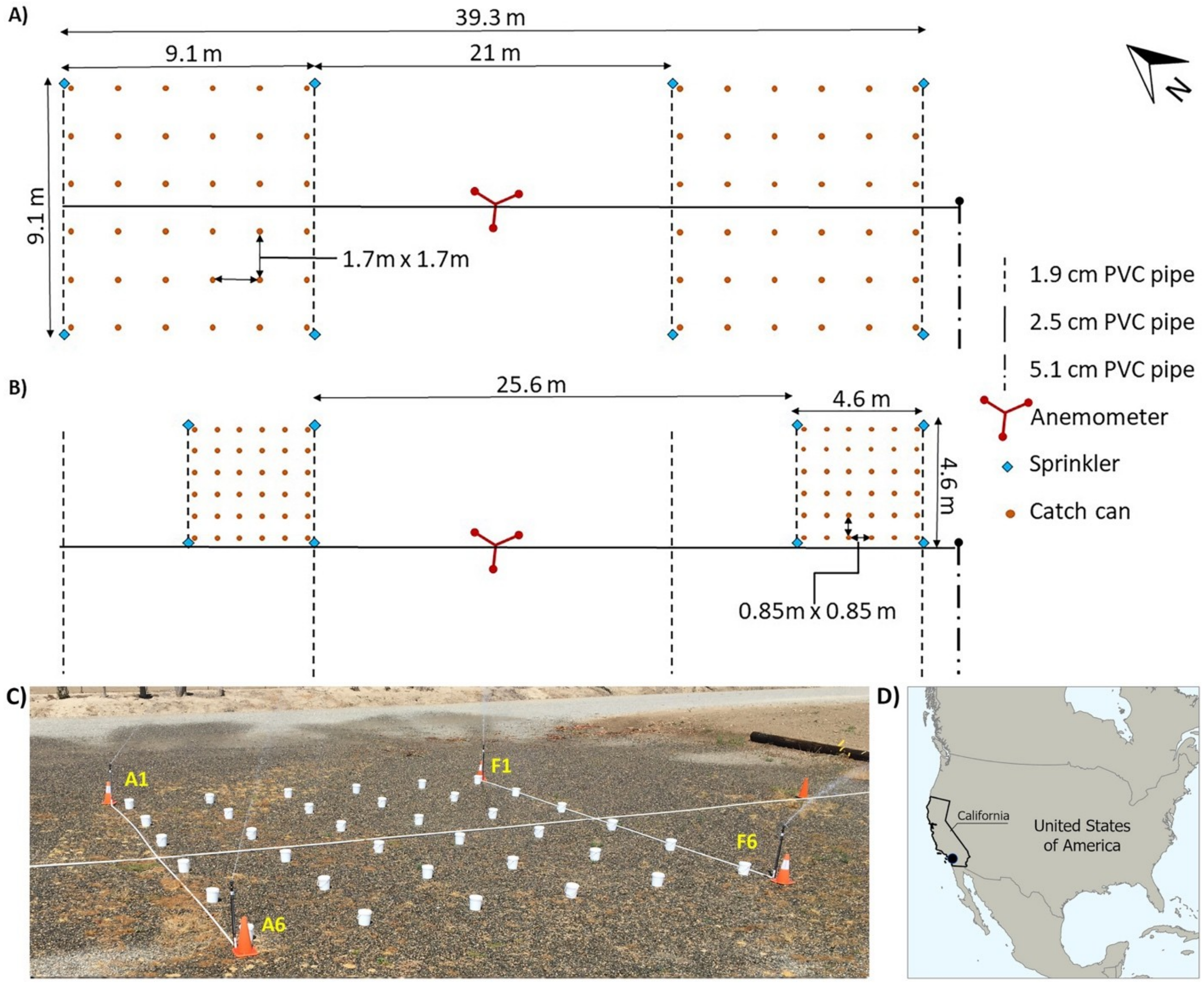

Figure 1: Schematic of the experimental setup for the large (9.1 m x 9.1 m) (A) and small (4.6 m x 4.6 m) spacing (B). Photo of experimental plot (C) and map location of study site (D).

Catch-can tests were conducted simultaneously in both plots, and during each test run two different sprinkler heads were compared. For each experiment, the sprinklers were run for 30 minutes. The water volume collected in each catch-can was measured immediately after the conclusion of the run using either a 250 mL or a 500 mL graduated cylinder to minimize evaporation losses from the collectors. Each experiment was repeated three to five times which resulted in 113 runs for the large spacing experiments and 76 runs for the small spacing experiments. The collected water depth (mm) was calculated by dividing the volume (L) caught by the opening area of the catch-can (m^2). Additionally, the application rate (mm/h) was calculated by dividing the average water depth (mm) collected by all 36 catch-cans by the experiment's run time (h).

Wind speed (km/h) was recorded every minute during the experiment, and the average wind speed was calculated for each 30-minute run. Operating pressure measurements were taken twice during each run at the main valve using a hand-held pressure gauge (Dwyer DPGWB-08 or a Dwyer DPG-005). Additionally, two pressure measurements were recorded at one sprinkler riser of each model just upstream of the pressure regulator. The operating pressure reported for each run was determined as the average of these last two measurements.

Table 1: Manufacturer specifications of each sprinkler model.

Type	Model	Pressure regulator	Nozzle Diameter (mm)	Flow rate (L/h)	Spray radius (m)
		4.6 m x 4.6 m spacing			
MSMT(1)	Hunter MP2000-360	Hunter 276 kPa (40 psi)	-	336.1	5.9
	K-Rain RN200	Rainbird 310 kPa (45 psi)	-	408.8	5.6
	RainBird R-VAN 18-360	Rainbird 310 kPa (45 psi)	-	420.2	5.2
	Toro PRN-F	Rainbird 310 kPa (45 psi)	-	642.8	6.7
		9.1 m x 9.1 m spacing			
MSMT(1)	Hunter MP3000-360	Hunter 276 kPa (40 psi)	-	826.7	9.1

Geared rotor	Nelson R2000LP-plate WF18- nozzle #18	Nelson 207 kPa (30 psi)	3.57	726.8	11.7
	Rainbird 5000Plus-nozzle 1.5	Rainbird 310 kPa (45 psi)	-	349.7	10.7
Impact	Rainbird LF2400 13° Maroon deflector & 09 silver nozzle	Senninger 207 kPa (30 psi)	3.57	742.7	11.0
	Rainbird 2045PJ-SBN-1 1/8” blue nozzle	Senninger 207 kPa (30 psi)	3.18	692.7	11.1
Wobbling sprinklers	XCEL- Wobbler HA- 5/32” turquoise nozzle (#10)	Senninger 172 kPa (25 psi)	3.97	797.2	8.2

Flow rate and spray radius represent nominal data collected from the manufacturers. (1) Multi Stream Multi-Trajectory nozzle.

2.2 Calculation of distribution uniformity parameters

The collected catch-can data was used to calculate a set of uniformity parameters for each sprinkler model and run. The parameters used in the study are the low-quarter distribution uniformity (DU_{LQ}) and Christiansen’s Coefficient of Uniformity (CU) (Keller and Bliesner, 1990; Burt et al., 1997; Tarjuelo et al., 1999).

Distribution Uniformity, DU or DU_{LQ} (unitless):

$$DU_{LQ} = \frac{D_{LQ}}{\acute{D}} \tag{1}$$

Where D_{LQ} is the average depth of water (mm) collected by the lower quartile of all catch-cans and $\acute{D}$ is the average depth of water (mm) collected by all catch-cans.

Christiansen’s Coefficient of Uniformity (Christiansen, 1942), CU (unitless):

$$CU = 1 - \frac{\sum_{i=1}^{n} \left| D_i - \acute{D} \right|}{\sum_{i=1}^{n} D_i} \tag{2}$$

Where D_i is water depth (mm) collected by each catch-can, $\acute{D}$ is the average depth of water (mm) collected by all catch-cans, and n is the total number of cans used in each run.

The distribution uniformity can be used to estimate how much water needs to be applied to reach a desired irrigation target. To calculate the additional water required to offset losses due to distribution non-uniformity, the gross water amount (I_{gross}) (mm or m^3) (Mohamed et al., 2019) is calculated as:

$$I_{gross} = \frac{I_{Net}}{DU_{LQ}} \tag{3}$$

Where I_{Net} represents the desired irrigation target (mm or m^3) and DU_{LQ} (unitless) the distribution uniformity of the sprinkler model.

Using I_{gross} (mm) allows calculating the time (I_{time}) (hours) needed to reach a certain irrigation target (I_{Net}), which depends on DU_{LQ} and the application rate (mm/hour) a of a sprinkler. Knowing I_{time} might help the user in making decisions on what area can be effectively irrigated with a certain sprinkler model per unit time. I_{time} also allows operators to assess the tradeoff between the amount of water needed to reach I_{gross} versus the amount of time needed to reach I_{gross}. A lower DU_{LQ} means more water must be applied to ensure most containers reach at least I_{Net} whereas a higher application rate allows reaching I_{Net} faster. I_{time} is calculated as follows:

$$I_{time} = \frac{I_{gross}}{a} \tag{4}$$

Where a is the application rate of the sprinkler model and I_{gross} is the gross water amount that needs to be applied to reach a desired irrigation target (I_{Net}).

The ten sprinkler models tested in this study all had different spray radii listed in Table 1. Testing these sprinklers with a static plot setup (e.g. 4.6 m x 4.6 m and 9.1 m x 9.1 m) results in different percentages of overlap in spray area of the four sprinklers installed at the corners of each plot, which can be calculated as follows:

$$\% Spacing = \frac{D}{L} * 100 \tag{5}$$

Where L (meters) is the spacing of the sprinklers (e.g. 4.6 m or 9.1 m for the small and large experimental plot size, respectively) and D (meters) is the spray diameter of the sprinkler model listed in Table 1. The sprinklers' overlap in spray area decreases as the spacing increases.

Most nurseries in California arrange outdoor plant containers in 15 ft by 15 feet (4.6 m x 4.6 m) to 30 ft by 30 ft (9.1 m x 9.1 m) plots to provide plant-specific irrigation and because of labor and mechanization considerations. These plot sizes did not only motivate the experimental design of this study, but also allow calculation and comparison of the total amount of water used by each sprinkler type to reach a given irrigation target (I_{Net} in L) irrespective of the overlap in spray area between sprinklers. To calculate the total water amount needed to meet an I_{Net} = 10 mm irrigation target for the two experimental plot sizes used in this study (i.e. 4.6 m x 4.6 m and 9.1 m x 9.1 m) and knowing that four sprinklers were installed at the corners of each plot, the total water use, U, in liters to irrigate the experimental plot area can be calculated as follows:

$$U = A * I_{gross} \tag{6}$$

Where A is the area (m^2) of the experimental plot used in this study (e.g. 4.6 m x 4.6 m or 9.1 m x 9.1 m) listed in Table 1 and I_{time} (hours) is the calculated time to reach I_{Net} = 10 mm using the average distribution uniformity ($D\acute{U}_{LQ}$) and application rate, a, (mm/hour) measured for that sprinkler model.

While evaporation was not directly measured during the catch-can experiments, it is not expected to significantly impact the distribution uniformity of the different sprinkler models. However, it is likely that the actual application rates of the catch-can tests were slightly higher than the measured rates due to small evaporation losses, particularly for the catch-can tests conducted during the summer months. Daily average values of reference evapotranspiration recorded on the experimental dates can be found in Table S1.

3 Results

3.1 *Comparison of uniformity parameters by sprinkler model*

Distribution uniformity (DU_{LQ}) observed across the 189 catch-can tests ranged from 0.47 to 0.86, with mean values ranging from 0.58 to 0.78, highlighting the variability in irrigation distribution across the tested overhead sprinkler models (Table 2). Compared to DU_{LQ}, Christiansen's uniformity coefficients (CU) exhibited over a narrower range, from 0.65 to 0.92, and mean CU values ranged from 0.74 to 0.88. CU values consistently exceeded DU_{LQ} for all catch-can trials because DU_{LQ} only considers the lowest quarter of all 36 catch-cans, focusing on those collecting the least amount of water. In contrast, while CU represents the spread of collected water around the mean water amount collected by all catch-cans. Very low values in DU_{LQ}, as shown in Figure 2, are generally associated with high wind speeds, yielding DU_{LQ} and CU values much lower than the average measurements.

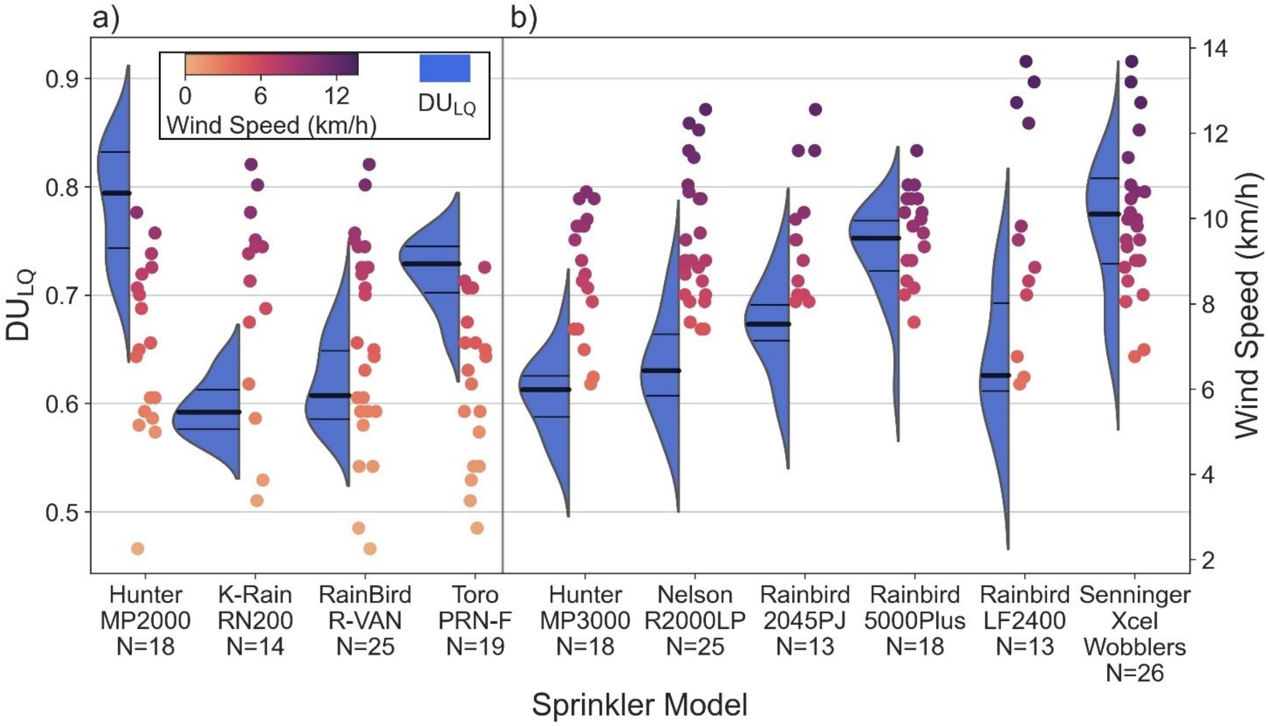

Figure 2: Violin plots of distribution uniformity (DU_{LQ}) and graduated color plots of wind speeds (km/h) observed during the catch-can tests comparing the ten sprinkler models in the small (4.6 m x 4.6 m) (a) and large (9.1 m x 9.1 m) spacing (b). The left side of the violin plots show the variation in DU_{LQ} across all catch-can experiments conducted for each model. The right

side of the violin plots show the wind speeds observed during the experiments. Solid black lines show the median value and interquartile (25th – 75th percentile) range for each sample.

Among the ten sprinkler models tested, the Hunter MP2000 ($D\acute{U}_{LQ}$ = 0.78; $C\acute{U}$= 0.88) exhibited the highest irrigation efficiency, closely followed by the Senninger Xcel Wobbler ($D\acute{U}_{LQ}$= 0.76; $C\acute{U}$ = 0.85). The Toro-PRN and Rainbird 5000 Plus achieved comparable uniformities with $D\acute{U}_{LQ}$ and $C\acute{U}$ exceeding 0.72 and 0.74, respectively. The sprinkler models with the lowest measured distribution uniformities ($D\acute{U}_{LQ} < 0.62$; $C\acute{U} < 0.76$) were the K-Rain and RainBird R-VAN tested in the small spacing, and the Hunter MP3000, the Nelson R2000LP, and the Rainbird LF2400 tested in the large spacing.

Variability in distribution uniformity within and across sprinkler models revealed complex patterns. Among the sprinkler models with the highest $D\acute{U}_{LQ}$and $C\acute{U}$, the Toro PRN-F and Rainbird 5000Plus showed minimal interquartile ranges, indicating more consistent performance over multiple catch-can tests and under varying wind speeds, compared to the Hunter MP2000 and Senninger Xcel Wobbler (Figure 2). In contrast, the Rainbird LF2400 exhibited the greatest variability in DU_{LQ} and CU across test runs, potentially attributed to the Rainbird LF2400 trials experiencing the highest wind speeds among all trials and the greatest range in wind speeds observed across all sprinklers (Figure 2). Additionally, the number of catch-can trials varied between models, ranging from N=13 for the Rainbird LF2400 to N=26 for the Senninger Xcel Wobbler. Although we expected smaller interquartile ranges for models with fewer trials, and vice versa, our results did not reveal any clear relationship between the number of trials and the variability of uniformity metrics (Figure 2).

3.2 Effect of wind speed on distribution uniformity

As expected from previous studies, wind speed significantly influenced the distribution uniformity of half the sprinkler models tested ($p<0.05$ for 5 models). For the small spacing tests, the DU_{LQ} values for the Rainbird R-VAN, Toro PRN-F, and K-Rain RN200 remained relatively stable against varying wind speeds, ranging from approximately 2 km/h to 12 km/h (Figure 3). The $D\acute{U}_{LQ}$ for these models were 0.62, 0.72, 0.58, respectively, with minimal variation around the mean as indicated by a small standard deviation of less than 0.04 (Table 2). The linear regression slopes of DU_{LQ} against wind speed for these models ranged between -0.019 and 0.002 (Table 3), indicating a negligible impact of wind speed on distribution uniformity. In contrast, the Hunter MP2000 exhibited greater sensitivity to wind speed as indicated by DU_{LQ} values declining significantly at wind speeds greater than 9 km/h, despite maintaining the highest DU_{LQ} (>0.73) at lower wind speeds (Figure 3).

For the six sprinkler models tested with the larger spacing, DU_{LQ} generally decreased with increasing wind speed. Wind speeds in these plots ranged between 6 km/h and 14 km/h. The $D\acute{U}_{LQ}$for the Hunter MP3000, Nelson R2000LP, Rainbird 2045PJ, Rainbird LF2400, and Senninger Xcel Wobblers ranged between 0.60 and 0.76, with standard deviations ranging between 0.04 and 0.09. For these models, the linear regression slope between DU_{LQ} and wind speed ranged between -0.015 and -0.029. Among these models, the Senninger Xcel Wobblers consistently achieved the highest DU_{LQ} at all observed wind speeds. The other four models (e.g., Nelson R2000LP, Hunter MP3000, Rainbird LF2400, and Rainbird 2045PJ) generally had DU_{LQ} values below 0.7, which decreased with increasing wind speeds. In contrast, the Rainbird 5000Plus demonstrated better performance under higher wind speeds, with a much smaller regression slope (-0.008, p=0.453), comparable to that of the sprinkler models tested in the small spacing. Notably, the mean wind speeds recorded during the large spacing experiments (8.75 - 9.93 km/h) were higher than those observed in the small spacing experiments (6.12 – 8.01 km/h). Additionally, wind speeds higher than 12 km/h were never observed in the small spacing experiments, while wind speeds lower than 6 km/h were not recorded for the large spacing experiments.

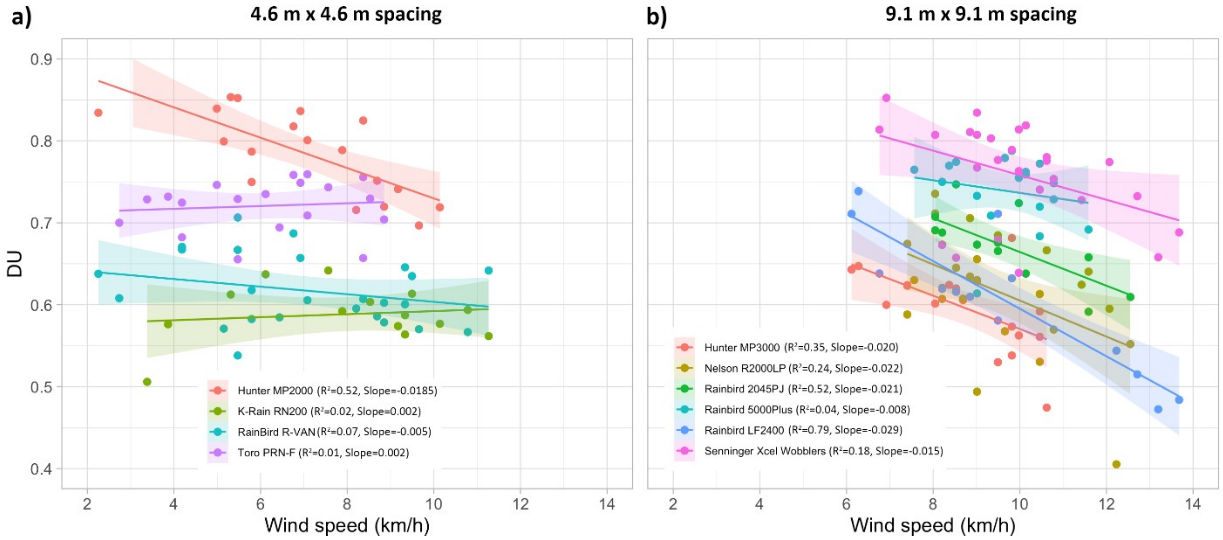

Figure 3: Relationship of distribution uniformity (DU_{LQ}) and wind speed for the ten sprinkler models tested in the small (4.6 m x 4.6 m) (a) and large (9.1 m x 9.1 m) spacing (b). Lines indicate linear regressions fit to the data pairs with fit equations provided in Table 3. Please note value ranges shown on the x-axes.

3.3 Water distribution observed on experimental plots

For the small spacing experiments, maximum catch-can volumes were observed near the center of the experimental plots, with variations in the distribution towards the edges depending on the sprinkler model. Consistent with the DU_{LQ} and CU findings, the Hunter MP2000 and Toro PRN-F exhibited the most evenly distributed catch-can volumes across the experimental plot, with most catch-cans averaging between 300 and 450 mL per 30-min run. In contrast, the RainBird R-VAN and K-Rain RN200 showed more variable spatial distribution uniformity, with water volumes dropping radially from 450 mL at the center of the experimental plot towards the edges. The standard deviation of the water volume collected by each catch-can across run also varied significantly between sprinkler models. The Hunter MP2000 had the lowest standard deviations, with consistent volumes towards the center of the experimental plot but higher variability at the eastern corner . Despite similar distribution uniformity, the Toro PRN-F and RainBird R-VAN had the greatest variability between runs, with relatively large standard deviations at the perimeter of the experimental plot (Figure 4a).

In the large spacing tests, there was substantially greater spatial variability in catch-can volumes between sprinkler models and runs. For all models, the upper right (east-facing) region consistently captured higher volumes of water, while the lower left (west-facing) region consistently captured lower volumes. This pattern aligns with the observed wind direction, which ranged between 170º and 200º on all experimental days. The Senninger Xcel Wobbler, which had the highest DU_{LQ}, created a larger zone of low water capture than the other models in the western (lower left) quadrant of the experimental plot, with relatively high volumes captured directly adjacent to the sprinklers (Figure 4b). The Rainbird 5000Plus, which achieved the second highest DU_{LQ}, displayed the most homogeneous distribution of catch-can volumes across the plot. The remaining four models exhibited similar spatial distribution patterns but varied in consistency between runs. For the Nelson R2000LP and Hunter MP3000, standard deviations were comparable, with higher variability in the eastern region of the plot and lowest in the west. The Rainbird 2045PJ was the most consistent model across runs, while the Rainbird LF2400, the model with the lowest DU_{LQ}, showed the most variability in catch-can volumes between runs, especially in the eastern quadrant of the experimental plot. While wind speed may be responsible for most inter-trial variation, the consistent wind direction (170º and 200º) across all experimental days does not fully explain variability between trials.

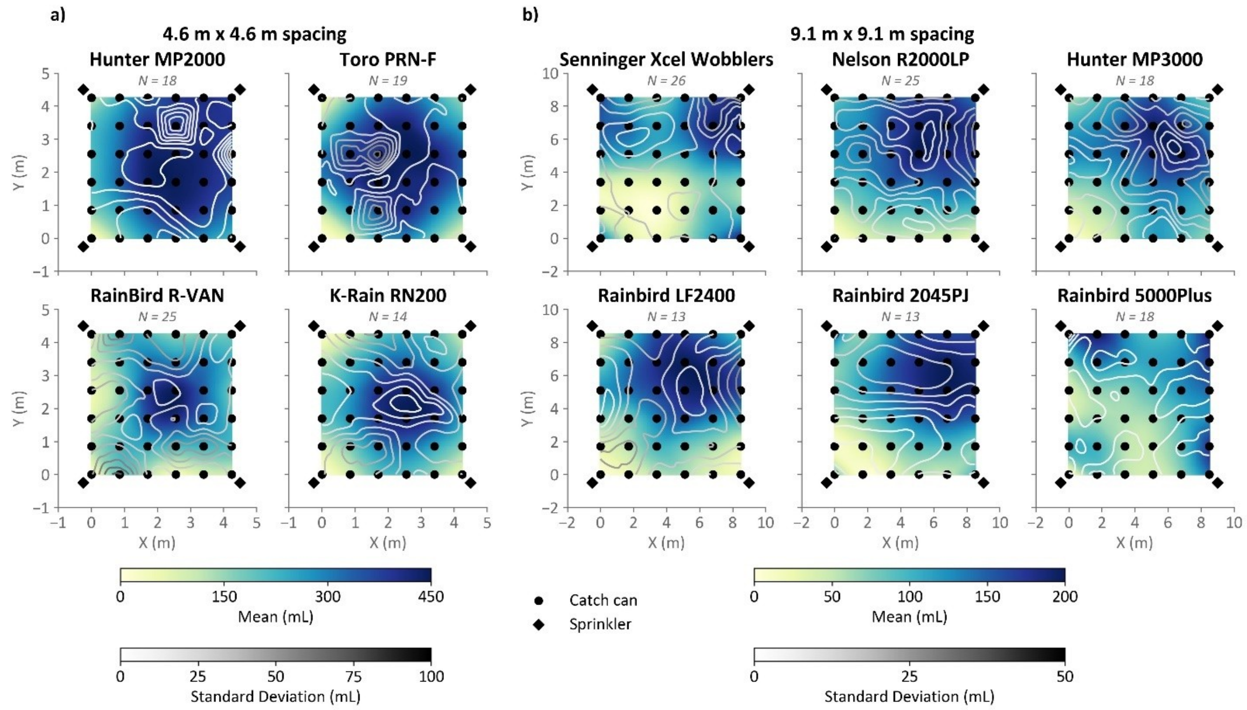

Figure 4: Interpolated mean water volumes (color maps) observed in each of the 36 catch-cans averaged over all runs conducted for each sprinkler model tested in the small (4.6 m x 4.6 m) (a) and large (9.1 m x 9.1 m) spacing (b). Contour lines show the standard deviation observed in catch-can volumes across all runs for each model.

3.4 Effect of operation parameters on distribution uniformity

Operating pressures in the main water supply line ranged between 345 kPa to 469 kPa for all runs in the small spacing experiments, and between 207 to 407 kPa for the large spacing experiments. As listed in Table 1, each sprinkler type was equipped with a pressure regulator set to the manufacturer-recommended pressure, ensuring that the minimum pressures were maintained within in the range of 276 kPa - 310 kPa for the small spacing and 172 kPa - 310 kPa for the large spacing, as recommended by the manufacturers. In the small spacing experiments, 310 kPa pressure regulators were installed for all models except the Hunter MP2000, which was fitted with a 275 kPa regulator. In the large spacing experiments, pressure regulators were set at different pressures ranging from 172 kPa (Senninger Xcel Wobbler) to 310 kPa (Rainbird 5000Plus), depending on the model. The measured pressure never fell below the manufacturer’s recommended value for each model (Figure 5).

The results indicate that the pressure regulators generally performed as intended, with none of the tested sprinkler models except for the Rainbird LF2400 showing sensitivity in DU to changes in operating pressure (Figure 5a & 5b). In the small spacing experiments, operating pressure did not significantly influence DU, as indicated by the non-significant slopes of linear regression models, which ranged between -0.00019 (Hunter MP2000) and 0.00049 (K-Rain RN200) (Table 3). Among the models tested in the small spacing, the K-Rain RN200, which overall exhibited the lowest DU_{LQ}, appeared to be the most sensitive to operating pressure, as indicated by its slope of 0.00049 ($p = 0.11$; Table 3). In contrast, the Toro PRN-F, which achieved the second highest DU, showed no relationship to operating pressure, as exhibited by a slope of just 0.00001 (Table 3).

For the models tested in the large spacing, the relationship between DU and operating pressure was generally non-significant, further indicating that the pressure regulators were functioning correctly. Slopes of linear regressions fit to the mean operating pressure measured just upstream of the sprinkler pressure regulator andDU data pairs ranged from -0.0001 (Rainbird 5000Plus) to 0.00068 (Rainbird LF2400) (Figure 5b). The Senninger Xcel wobbler, which showed the highest DU among all models tested in the large spacing, demonstrated no relationship between DU and operating pressure. In contrast, the Rainbird LF2400, which exhibited the lowest DU, appeared to be the most sensitive to operating pressure as indicated by the slope of 0.00068 ($p=0.049$; Table 3).

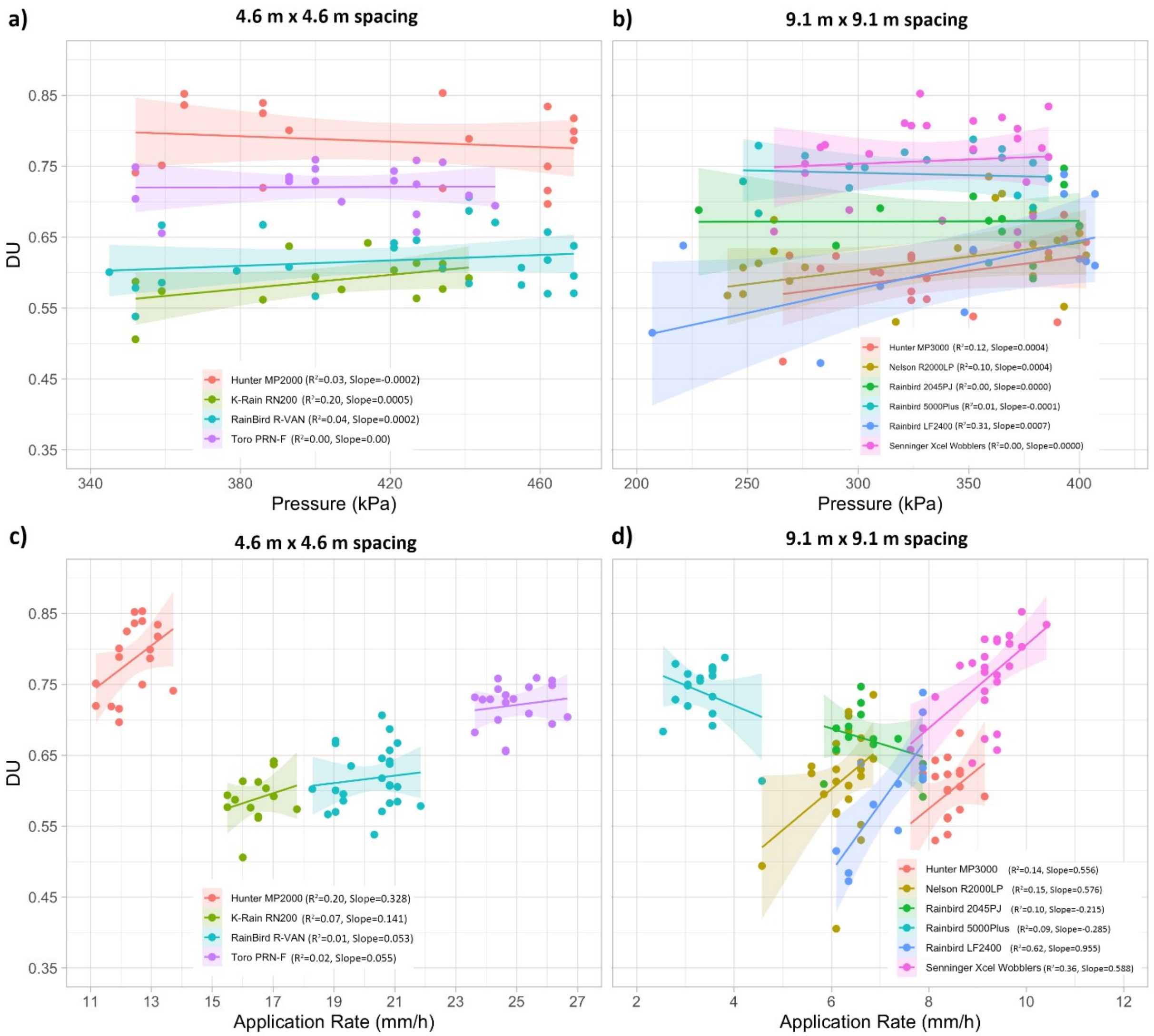

Figure 5: Relationship of distribution uniformity (DU_{LQ}) and operating pressure (a, b) and application rate (c, d) for the ten sprinkler models tested in the small (4.6 m x 4.6 m) and large (9.1 m x 9.1 m) spacing. Lines indicate linear regressions fit to the data pairs with fit equations provided in Table 3.

The results suggest that for most sprinkler models, DU is positively related to sprinkler application rate (Figure 5c & 5d). For all models except the Rainbird5000Plus and the Rainbird 2045PJ, a positive albeit non-significant slope was observed between DU and application rate (Table 3). For these models, both DU and application rate increased when wind speed decreased during the test runs. All sprinkler models tested with the small spacing achieved average application rates that were nearly double the application rates of sprinklers tested with the large spacing. This is expected because the sprinklers tested in the small experiment were positioned in a tighter spacing (i.e. more sprinklers per unit area), which results in higher application rates per unit area.

The application rate appears to be slightly positively correlated to DU in the small spacing. In this configuration, the slopes of linear regressions fit to the application rate vs. DU ranged from 0.134 (Rainbird R-VAN) to 0.833 (Hunter MP2000) (Figure 5c and Table 3). The mean application rate for each model tested in the small spacing ranged from 12.4 (Hunter MP2000) to 24.9 mm/h (Toro PRN-F). Among the four sprinkler models tested with the small spacing, the HunterMP2000 performed much better than the other MSMT models in terms of DU but showed a much lower application rate of 12.4 mm/h compared to the 16.4-24.9 mm/h of the other three MSMT models.

For the sprinkler models tested in the large spacing, the application rate had a greater positive correlation with DU for all models except the Rainbird 5000Plus and Rainbird2045PJ. For these two models, the application rate was rather negatively correlated to DU as evidenced by slopes of -0.2852 and -0.212, respectively. For all other models the slope of the relationship between application rate and DU ranged from 0.556 (Hunter MP3000) to 955 (Rainbird LF2400) (Figure 5d), while mean application rates ranged from 3.3 (Rainbird 5000Plus) to 9.2 mm/h (Senninger Xcel Wobbler). Both the Hunter MP3000 (MSMT) and Senninger Xcel Wobblers generally achieved the highest application rates, while the geared rotor models demonstrated the lowest application rates, and the application rates of the impact models were found in the middle. The Senninger Xcel Wobbler showed the highest application rate despite being installed at a spacing higher than the sprinkler radius (i.e. higher than 50% of throw diameter).

Table 2: Summary of experimental conditions, uniformity parameters and irrigation performance measures for each sprinkler model. DU_{LQ} is the low-quarter distribution uniformity and CU is the Christiansen's Coefficient of Uniformity. Uniformity metrics state the mean value and standard deviation calculated over all test runs. % spacing relative to throw diameter was calculated by dividing the spray diameter D by the plot length L of the small (4.6 m) and large spacing (9.1 m) experiments. I_{gross} was estimated assuming a target irrigation amount of I_{Net}=10 mm and each sprinkler's $D\acute{U}_{LQ}$, I_{time} is the time needed to reach I_{gross}, and U is the estimated total water amount each sprinkler model uses to reach INet=10 mm in the small and large spacing experimental plot.

Type	**Model**	**Number of tests**	**DU_{LQ}**	**CU**	**Application rate (mm/h)**	**Wind speed (km/h)**	**Pressure (kPa)**	**Spacing relative to throw diameter (%)**	**I_{gross} (mm) for I_{Net} = 10 mm**	**I_{time} (h)**	**Water use, U (L)**
MSMT(1)	Hunter MP2000-360	18	0.78±0.05	0.88±0.03	12.4±0.7	7.03±2.03	419.81±44.49	39.7	12.82	1.06	271.3
	K-Rain RN200	14	0.58±0.03	0.74±0.02	16.4±0.7	8.01±2.48	403.34±31.28	40.8	17.24	1.04	364.8
	Rainbird R-VAN 18-360	25	0.62±0.04	0.75±0.03	20.2±0.9	7.06±2.41	420.03±42.73	44.4	16.13	0.80	341.3
	Toro PRN-F	19	0.72±0.03	0.84±0.02	24.9±0.9	6.12±1.86	406.43±28.75	34.4	13.89	0.56	293.9
MSMT(1)	Hunter MP3000-360	18	0.60±0.05	0.75±0.03	8.4±0.3	8.74±1.45	333.29±44.09	50.3	16.67	1.98	1380.4
Geared rotor	Nelson R2000LP-plate WF18- nozzle #18	25	0.62±0.07	0.75±0.05	6.2±0.5	9.53±1.57	332.19±57.81	39.2	16.13	2.60	1335.7
	Rainbird 5000Plus- nozzle 1.5	18	0.74±0.04	0.82±0.05	3.3±0.5	9.68±1.06	327.31±47.16	43.1	13.51	3.14	1118.8
Impact	Rainbird LF2400 13° Maroon deflector & 09 silver nozzle	13	0.61±0.09	0.74±0.06	7.2±0.7	9.64±2.60	342.09±69.9	41.9	16.39	2.31	1357.3
	Rainbird 2045PJ- SBN-1 1/8" blue nozzle	13	0.67±0.04	0.78±0.03	6.7±0.6	9.6±1.51	350.04±49.01	41.3	14.93	2.23	1236.4
Wobbling nozzles	Senninger Xcel- Wobblers HA- 5/32" turquoise nozzle (#10)	26	0.76±0.06	0.85±0.03	9.2±0.6	9.93±1.71	326.06±55.41	56.4	13.16	1.43	1089.8

(1) Multi Stream Multi-Trajectory nozzle sprinkler.

Table 3: Summary of linear regression model metrics for DU_{LQ} versus observed wind speed and operating condition factors.

Sprinkler type	Model	Number of runs	Wind speed			Pressure			Application rate		
			R^2	Slope	p-value	R^2	Slope	p-value	R^2	Slope	p-value
4.6 x 4.6 m spacing											
MSMT(1)	Hunter MP2000-360	18	0.52	-0.019	0.00*	0.03	-0.0002	0.52	0.20	0.3280	0.07
	K-Rain RN200	14	0.02	0.002	0.65	0.20	0.0005	0.11	0.07	0.1410	0.35
	Rainbird R-VAN 18-360	25	0.07	-0.005	0.21	0.04	0.0002	0.36	0.01	0.0527	0.58
	Toro PRN-F	19	0.01	0.002	0.68	0.00	0.0000	0.96	0.02	0.0546	0.52
9.1 x 9.1 m spacing											
MSMT(1)	Hunter MP3000-360	18	0.35	-0.020	0.01*	0.12	0.0004	0.16	0.14	0.5560	0.12
Geared rotor	Nelson R2000LP-plate WF18-nozzle #18	25	0.24	-0.022	0.01*	0.10	0.0004	0.13	0.15	0.5760	0.05
	Rainbird 5000Plus- nozzle 1.5	18	0.04	-0.008	0.45	0.01	-0.0001	0.77	0.09	-0.2850	0.22
Impact	Rainbird LF2400 13° Maroon deflector & 09 silver nozzle	13	0.79	-0.029	0.00*	0.31	0.0007	0.05*	0.62	0.9550	0.00*
	Rainbird 2045PJ- SBN-1 1/8” blue nozzle	13	0.52	-0.021	0.01*	0.00	0.0000	0.98	0.10	-0.2120	0.29
Wobbling	Senninger XCEL- Wobblers HA-5/32” turquoise nozzle (#10)	26	0.18	-0.015	0.03*	0.00	0.0000	0.97	0.36	0.5880	0.00*

Note: * significant at alpha=0.05

3.5 Total water use and irrigation efficiency measures

While DU_{LQ} is an important performance measure when selecting a sprinkler type for a specific application, understanding the irrigation time (I_{time}) needed to reach a given irrigation target (I_{gross}) can help growers balance irrigation uniformity with the time needed to sufficiently irrigate a given area to meet I_{Net}. This balance is particularly important for larger irrigation areas or nurseries, where timely irrigation is crucial for maintaining profitability. A sprinkler with a lower DU_{LQ} requires more water to ensure most containers receive at least I_{Net}. For instance, with the Senninger Xcel Wobbler having a $D\acute{U}_{LQ}$ of 0.76 and an assumed irrigation target of I_{Net} =10 mm, the gross irrigation amount (I_{gross}) required is13.2 mm (Table 2). This means that 13.2 mm of water need to be applied to reach the 10 mm irrigation target. Considering the application rate, a, of the Senninger Xcel Wobblers as an example (9.2 mm/h; Table 2), the time needed to reach an I_{gross} of 13.2 mm is 1.43 hours (Table 2).

Among the sprinklers tested in the small spacing, the Toro PRN-F had the shortest irrigation time (0.56 h) and the second highest $D\acute{U}_{LQ}$ (0.72); in contrast, the Hunter MP2000-360 had the longest irrigation time (1.06 h) and the highest $D\acute{U}_{LQ}$ (0.78). Of the sprinklers tested in the large spacing, the Senninger Xcel Wobblers had the shortest irrigation time (1.43 h) and the highest $D\acute{U}_{LQ}$ (0.76), while the Rainbird 5000Plus had the longest irrigation time (3.14 h) and the second highest $D\acute{U}_{LQ}$(0.74) (Tables 2). These results suggest that while DU_{LQ} and irrigation time are not directly correlated, application rate and the time required to reach a target irrigation amount are important factors when choosing a sprinkler model with high irrigation uniformity.

Because this experiment was conducted using two fixed plot sizes (4.6 m x 4.6 m and 9.1 m x 9.1 m), the sprinkler models had varying degrees of overlap in their spray area, influenced by each sprinkler's nominal spray radius (Table 1). For the four models tested in the small spacing (4.6 m x 4.6 m), the percent spacing relative to throw diameter provided by the manufacturer varied between 44.4% (Rainbird R-VAN) and 34.4% (Toro PRN-F) (Table 2).The Toro PRN-F, which had the greatest overlap in spray area, also achieved the highest application rate and second highest $D\acute{U}_{LQ}$ among the four models tested in the small spacing. Among the models tested in the large spacing (9.1 m x 9.1 m), the percent spacing varied between 56.4% (Senninger Xcel) and 39.2% (Nelson R2000LP)(Table 2). The Senninger Xcel was the only sprinkler with a spacing percentage higher than 50%, while the Nelson R2000LP, Rainbird 5000Plus, the Rainbird LF2400 and Rainbird 2045PJ had similar percentages of around 42%.

Assuming I_{Net} = 10 mm and using the observed $D\acute{U}_{LQ}$, the total water use for four sprinklers set up in the small spacing ranged between 271.3 L (Hunter MP2000) and 364.8 L (K-Rain RN200). In the large (9.1 m x 9.1 m) spacing tests, total water use ranged between 1089.9 (Senninger Xcel) and 1380.4 L (Hunter MP3000). Total water use is determined by the DU of the irrigation system, while the application rate is influenced by the sprinkler's flow rate and spacing, as shown in Table 2.

A comparison of the Hunter MP3000, the RainBird LF2400 and the Nelson LP2000LP models, which were tested in the large spacing experiments, showed that despite similar DU (0.60, 0.61 and 0.62, respectively, Table 2), these models had different application rates (8.4 mm/h, 7.2 mm/h and 6.2 mm/h, respectively). This comparison shows that while DU primarily affects total water use (1380 L, 1357 L and 1336 L, respectively), the application rate determines irrigation time. These results indicate that regardless of nozzle size, flow rate, or application rate, some sprinkler models achieve higher DU and therefore minimize water loss.

3.6 Christiansen's Coefficient of Uniformity and Distribution Uniformity

Distribution uniformity (DU_{LQ}) was well correlated to the Coefficient of Uniformity (CU) (Figure 6), such that the sprinkler models that demonstrated the best irrigation uniformity based on DU_{LQ} also aligned with the results based on CU. DU_{LQ} only considers the lowest quarter of all 36 catch-cans, focusing on those collecting the least amount of water, while CU represents the overall distribution of the summed absolute deviations around the mean collected by all catch-cans. Therefore, sprinklers with higher DU_{LQ} relative to CU, based on a linear regression of DU_{LQ} versus CU for all experiment runs, distributed water more uniformly in the areas that received the least amount of water, although overall uniformity for all catch-cans was comparatively lower. Sprinklers in this category included impact sprinklers and geared rotor sprinklers, such as the Rainbird LF2400 (DU_{LQ} = 0.61; CU = 0.74), R-VAN (DU_{LQ} = 0.62; CU = 0.75), 5000Plus (DU_{LQ} = 0.74; CU = 0.82), and 2045PJ (DU_{LQ} = 0.67; CU = 0.78). Conversely, sprinklers with higher CU than DU_{LQ} in the linear regression distributed water more uniformly overall but lacked uniformity in the areas that received the least water. All sprinklers in this category were MSMT sprinklers (K-Rain RN200, Hunter MP3000, MP2000, and TORO PRN), suggesting that this may be characteristic of the MSMT technology, although the Rainbird R-VAN did not exhibit the same behavior.

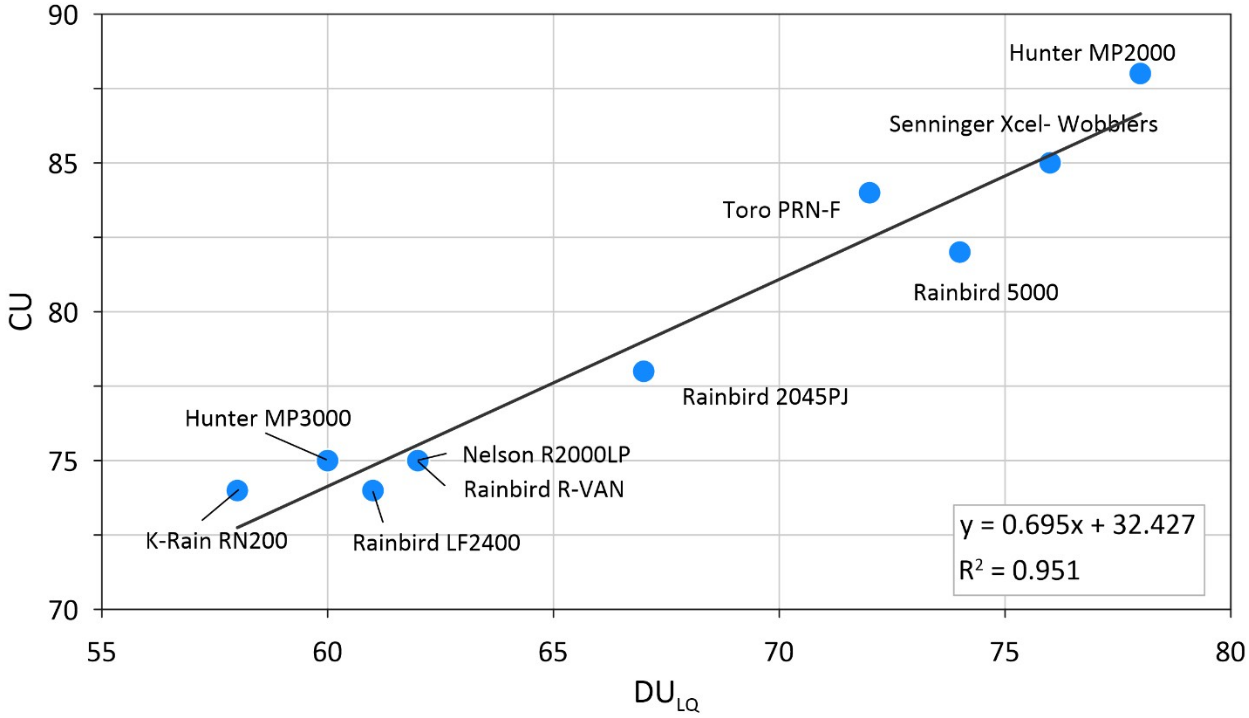

Figure 6: Relationship between distribution uniformity (DU_{LQ}) and Christiansen’s Coefficient of Uniformity (CU).

4 Discussion

4.1 Factors influencing irrigation uniformity metrics

Among the ten tested sprinkler models, the Hunter MP2000 and Senninger Xcel Wobbler demonstrated the highest uniformity across all uniformity metrics. Notably, the Hunter MP2000, categorized as an MSMT (multi-stream, multi-trajectory) model exhibited excellent uniformity in the small spacing, with DU_{LQ} exceeding 0.70 across all test runs (N=26). Of the five MSMT models tested, only the HunterMP2000 and Toro-PRN models demonstrated high uniformity, highlighting the importance of model selection in optimizing uniformity for the MSMT sprinklers.

In the large spacing tests, the sprinkler models exhibited greater deviations in distribution uniformity than the models tested in the small spacing, likely due to higher wind speeds observed. The Senninger Xcel Wobbler, a wobbling sprinkler, exhibited the highest uniformity, aligning with other studies that have found wobbler sprinklers to achieve superior uniformity compared to impact sprinklers, particularly in large container (27 cm diameter) and smaller container (17.6 cm diameter) nursery settings (Beeson and Knox, 1991; Million and Yeager, 2015). Additionally, the Senninger Xcel Wobbler's ability to deliver water at lower operating pressures offers an additional advantage for growers since it allows energy cost savings and to irrigate larger areas at the same time given a fixed pumping capacity. The Rainbird 5000Plus, a geared rotor sprinkler, also showed relatively high uniformity, followed by the Rainbird 2045PJ, an impact sprinkler.

Our research highlights the influence of wind speed on irrigation uniformity, depending on the model of sprinkler chosen. Consistent with previous research (Kumar et al., 2023; Montazar and Moridnejad, 2008), increased wind speeds generally had a negative impact on uniformity. This was particularly evident in the performance of the Hunter MP2000 in the small spacing tests and in all six models tested in the large spacing, except for the Rainbird 5000Plus. Interestingly, the Toro PRN-F, RainBird R-VAN, and K-Rain RN200 exhibited contrasting trends, showing no decrease in uniformity with varying wind conditions. This may be due to their high application rates (> 19 mm/h) and high operating pressures (310 kPa (45 psi)), which might have made the water jets more resistant to wind effects. Additionally, although statistically significant only for two models, higher application rates were associated with improved distribution uniformity across most sprinkler models, which is consistent with findings from previous studies (Khedr, 2020; Ashine et al., 2022). This correlation may be influenced by the experimental setup used in this study. High wind speeds displaced water droplets beyond the catch-can area, reducing the volume of water intercepted by the buckets and thus lowering the measured application rate. This phenomenon decreases DU, yielding a correlation between DU and application rate. Indeed, the two sprinkler models where this correlation was significant (RainBird LF2400 and Senninger Xcel Wobblers) experienced the highest wind speeds during testing (>13 km/h). In field conditions, water discharged by adjacent sprinklers may partially compensate for this effect, supporting the hypothesis that sprinkler overlap can mitigate wind-related losses. This is further supported by statistically significant negative correlations found between application rate and wind speed for three models (Hunter MP2000, Senninger Xcel Wobblers and RainBird LF2400) (data not shown). The Rainbird 5000Plus and Rainbird 2045PJ were the only models to show a decrease in uniformity with increasing application rate, although the correlation was not statistically significant. These trends reinforce the importance of choosing a sprinkler model that maintains a high DU even during high wind speed conditions.

4.2 Tradeoffs in sprinkler model selection

When selecting a sprinkler model for nursery operations, several factors need to be considered, including irrigation uniformity (DU_{LQ} and CU), operating pressure, flow rate, application rate, throw radius, irrigation time, and the number of sprinklers required to irrigate a given area. While higher distribution uniformity means less water needs to be applied to reach a target irrigation amount, sprinklers operating at higher pressures or those with larger nozzles may deliver higher flow rates, resulting in higher application rates and shorter irrigation times to reach a target irrigation amount. Conversely, a sprinkler with a lower application rate due to a smaller nozzle and lower flow rate may require more time to reach a certain irrigation target, which could limit how many blocks a nursery operator can irrigate in one day. On the other hand, sprinklers with higher application rates can cause more pressure losses in the supply lines, potentially reducing DU if the system is not properly designed. Therefore, tradeoffs between distribution uniformity and application rate have economic implications for nursery operations, as they influence total water depth and the time needed to irrigate a given area. Selecting the optimal sprinkler model requires balancing these parameters with irrigation objectives and project budget.

While application rate is a primary factor determining irrigation time, DU also plays a role since a greater water depth is required when DU is lower. Application rates in nursery sprinkler systems generally range from a minimum of 2.5 mm/h to over 25 mm/h, meaning application rate can have a tenfold effect on irrigation time, while DU can affect it to a lesser extent. For instance, a DU of 0.5 compared to a DU of 0.9 would require an increase of about 80% in irrigation time, which is still less than the tenfold increase observed with application rate.

Nursery managers generally prefer high application rates since these allow shorter irrigation times per block, enabling personnel to perform other tasks such as harvesting, weeding, pruning, etc. However, irrigation blocks with lower application rates could be irrigated simultaneously for longer periods, achieving essentially the same result in terms of total water depth applied as irrigating high application rate blocks sequentially. One drawback of this approach, though, is potentially increased evaporative losses due to larger areas being wetted for a longer period.

Most irrigation systems aim for a 50% spacing relative to the spray diameter between sprinklers (also called head-to-head irrigation). In this study, sprinklers were tested in two fixed plot sizes (4.6 m x 4.6 m, 9.1 m x 9.1 m), resulting in variable spacing percentage in between the sprinklers installed at the corners of the test plots (see Table 2). As a result of the experimental setup and the spray radii of the tested models, the spacing percentages ranged from 56.4% (Senninger Xcel) to 34.4% (Toro PRN-F). For any given nozzle flowrate, reducing the spacing between sprinklers, which increases the percent overlap in spray diameter, positively affects the application rate, since the nozzle's flowrate produced is distributed over a smaller area.

In this experiment, performance parameters were evaluated in an experimental plot consisting of only four sprinklers per model. Therefore, this setup likely underestimates the application rate compared to field conditions, where the four sprinklers would be surrounded by other sprinklers that would contribute to the water volumes intercepted by catch-cans in the experimental area. This underestimation is particularly true for sprinklers with radii much larger than the spacing, where large volumes of water were applied outside of the experimental area. The only sprinkler with a radius smaller than the spacing was the Senninger Xcel Wobbler, making its measured application rate representative of field conditions. The application rate may have been particularly underestimated for the Toro PRN-F and the Nelson R2000LP, which had the largest spray radii in each spacing (6.68 m and 11.7 m, respectively). Despite this, the Toro PRN-F showed the highest application rate (24.9 mm/h) of all models tested in the small spacing, which is expected given its highest flowrate. Conversely, the Senninger Xcel Wobbler achieved the highest application rate of all models tested in the large spacing by producing the second highest flowrate.

Interestingly, the Senninger Xcel wobbler also achieved the lowest total water use among all the sprinkler models tested in the large spacing. To reach an irrigation target of 10 mm, the Senninger Xcel wobbler required 1089 L (Table 2) for the 9.1 m x 9.1 m plot (Table 2). The second lowest water usage was achieved by the Rainbird 5000Plus with 1119 L, yet it required 3.14 hours of irrigation time to reach the 10 mm target, while the Senninger Xcel only required 1.43 hours. Due to the longer irrigation time and low application rate of the Rainbird 5000Plus, evaporative losses might play a larger role in the overall water savings, irrespective of its relatively high $D\acute{U}_{LQ}$, which was the second highest among the six sprinklers tested in the large spacing. Total water use among the four sprinklers tested in the small spacing followed a similar pattern. The Hunter MP2000, which had the highest $D\acute{U}_{LQ}$ (0.78), the lowest application rate (12.1 mm/h), and the longest irrigation time (1.05 h) to reach the irrigation target of 10 mm, best performing sprinkler in terms of total water used in the small spacing was the Hunter MP2000, , used the least water and had the second smallest spacing percentage (39.7%).

4.3 Uncertainties and limitations of experimental conditions

Our research demonstrates the relationship between performance parameters and the uniformity of various sprinkler models in nursery settings. However, when interpreting these results and their implications for sprinkler selection, it is important to consider the experimental design and conditions under which the models were tested.

First, the experiments were conducted at different times of the year, with tests on sprinklers in the large spacing conducted between March and July 2022 and tests on sprinklers in the small spacing conducted between September 2022 and May 2023 (section 2.1). Consequently, variations in environmental conditions, such as temperature, humidity, and wind patterns, could have influenced the performance of the sprinkler models. While some of these variables likely had negligible impact on the 30-min tests, seasonal changes may have introduced variability in the results, as discussed for wind speed in section 3.2. Additionally, the experiments did not include direct measurements of water loss due to evaporation. Since our method to calculate DU_{LQ} is affected by the absolute values collected in the catch-can, a slightly lower DU_{LQ} is expected due to evaporation losses. Although it is not expected that evaporative losses substantially impacted the DU_{LQ} during each test, they might explain some of the variability observed in the data between tests performed for the same model. For example, both the Nelson R2000LP and the RainBird R-VAN exhibited considerable vertical scatter in individual test results around the regression line of DU_{LQ} and wind speed, which could be related to differences in evaporation between test runs.

Second, sprinkler models were tested in a fixed plots size (small and large spacing), resulting in varying spacing percentages (34.4% to56.4%) relative to spray diameter between models. A greater overlap (lower percentage spacing relative to spray diameter) could have a positive effect on DU, particularly in windy conditions. While greater overlap in spray diameter might compensate for poor DU, it could also increase capital costs due to the need for additional irrigation lines, sprinkler heads, and other infrastructure associated with a tighter spacing. In this study's experiment setup, the relationship between spacing relative to diameter and DU could not be exactly determined, as tests were not performed at a constant (e.g., 50%) spacing relative to diameter. Future work therefore could focus on repeating the sprinkler tests under standardized spray spacing (e.g. 50%) to eliminate the influence of spray overlap on DU.

Another limitation of this study is the absence of plants in the containers during testing. It is well-established that the presence of plants can significantly impact distribution uniformity due to factors such as interception or canopy structure (Beeson and Knox, 1991; Boja et al., 2012;

Million and Yeager, 2015). Therefore, the results of the experiments may not fully reflect real-world conditions in nursery settings where plants are present.

When designing nurseries with sprinkler systems, optimizing water pressure uniformity to increase distribution uniformity is important for improving irrigation efficiency. In this study, variations in operating pressure in the sprinkler water lines had no impact on the sprinkler DU and the application rate because each sprinkler was equipped with a pressure regulator. However, this may be not be the case in commercial nurseries where pressure regulation technology is not universally adopted.

Lastly, while at least two sprinkler models were tested for each sprinkler type (e.g. MSMT, impact, rotary), only one model (Senninger Xcel) was tested for the wobblers, since this technology is exclusively available only from Senninger. Despite these limitations, the experiments provide valuable insights into the performance of different sprinkler models under controlled spacings and pressure conditions. Future research could expand upon these findings by conducting experiments across a broader range of wind speeds, including a wider range of sprinkler models, and incorporating additional factors such as plant presence, variations in water pressure, and measured evaporation.

5 Conclusions

This study provides a comparison of the irrigation uniformity of ten overhead sprinkler models commonly used in outdoor nurseries in California. The relative performance of each sprinkler was examined under different operating conditions and wind speeds, to determine the influence of these factors on sprinkler efficiency. A total of 189 catch-can tests were performed to assess and compare the distribution uniformity (DU) of these models using two different experimental plot sizes (4.6 m x 4.6 m and 9.1 m by 9.1 m).

Among all models tested, the highest DU was achieved by multi-stream multi-trajectory sprinklers (e.g. Hunter MP2000 and TORO PRN), “wobbling” sprinklers (e.g. Senninger Xcel wobblers), and gear-drive sprinklers (Rainbird 5000). These models use relatively recent innovations in technologies that outperform traditional impact sprinklers in terms of distribution uniformity. Multi-stream multi-trajectory sprinklers offer high distribution uniformity at an affordable price but have the limitation of non-interchangeable nozzles, resulting in a factory-determined application rate. Conversely, “wobbling” sprinklers provide high uniformity, interchangeable nozzles, and an affordable price, though they are limited by a fixed 360-degree arc.

While this study addressed several tradeoffs relevant to nurseries, future research could investigate additional sprinkler configurations, technologies, and other variables such as plant presence and spatial layout to offer a more comprehensive guide for nursery operators.

The compared models offer clear tradeoffs in DU and application rate, which nursery operators can consider when selecting models for their operations. To further assist the selection process, this study introduced two new selection criteria: a) different sprinkler spacings, affecting the number of sprinkler heads per area, and b) I_{time} (time to reach target irrigation amount). The time and number of sprinkler heads required to irrigate an area are necessary considerations relevant to a nursery’s profitability, scale, and efficiency. Paired with wind speed and operational factors, these criteria introduce several tradeoffs that highlight the importance of tailoring sprinkler selection to the specific conditions and needs of each nursery.

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Declaration of interests

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.

Author contributions

GS: conceptualization, data curation, funding acquisition, investigation, methodology; AB, WC, KG, SJ, KO, CPG, KR, KJZW: methodology, formal analysis, visualization, writing – original draft, writing – review & editing; HED: project administration, supervision, Writing – review & editing

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