Crop Protection 29 (2010) 561–566

Contents lists available at ScienceDirect

Crop Protection

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

Comparative performance of recycling tunnel and conventional sprayers using standard and drift-mitigating nozzles in dwarf apple orchards

L. Jamar[a,*], O. Mostade[b], B. Huyghebaert[b], O. Pigeon[c], M. Lateur[a]

[a] *Centre Wallon de Recherches Agronomiques (CRA-W), Département Sciences du vivant, rue de Liroux, 4, B-5030 Gembloux, Belgium*
[b] *CRA-W, Département Productions et filières, ch. de Namur, 146, B-5030 Gembloux, Belgium*
[c] *CRA-W, Département Agriculture et milieu naturel, rue du Bordia, 11, B-5030 Gembloux, Belgium*

ARTICLE INFO

Article history:
Received 1 July 2009
Received in revised form
14 December 2009
Accepted 15 December 2009

Keywords:
Air induction nozzle
Droplet size
Sedimentation drift
Spray cover
Spray deposition

ABSTRACT

The use of tunnel sprayers should be encouraged because they can potentially reduce pesticide input and drift in orchards. They could also allow smaller plot size in multifactorial trials in which fully randomized or randomized block designs are recommended. However, the effectiveness of plant protection products applied with tunnel sprayers cannot be reliably assessed without a thorough investigation into spray distribution in tree canopies. A set of three experiments was undertaken in an apple orchard to compare a new type of recycling tunnel sprayer with a standard axial fan sprayer, both of them fitted with either conventional hydraulic hollow cone nozzles (ATR) or drift-mitigating air induction cone nozzles (TVI). Its performance was assessed in terms of 1) spray deposit and coverage in the canopy, 2) sedimentation drift (spray drift to the ground) and 3) collection and recycling rate of the liquid sprayed in the tunnel. Artificial targets composed of cellulose papers and water-sensitive papers were used to evaluate the spray deposit and coverage at similar target positions for each treatment. A fluorescent dye was used as the spray tracer.

The study showed that, when using the ATR nozzles, the spray deposit, at each sampling point in the tree canopy, produced by the tunnel sprayer was not significantly different from that produced by the standard sprayer. The spray deposited on the top of the trees when using the TVI nozzles, however, was significantly less than with the standard sprayer. At the same spray deposit level, the spray cover on the canopy, estimated by image analysis, was relatively better with the standard sprayer than with the tunnel sprayer. At the same spray deposit level, the TVI nozzles resulted in significantly poorer spray cover of the canopy than the ATR nozzles. At low wind speeds, the sedimentation drift varied on average from 5.8 to 9.1% of the total sprayer output, irrespective of the type of sprayer or nozzle. The overall mean of the sedimentation drift was not significantly different for the two types of sprayers. The recovery system, which included a continuous recycling process in the tunnel sprayer, led to average savings of 28 and 32% of the applied spray mixtures for the ATR and TVI nozzles, respectively. The tunnel sprayer might therefore be suitable for small-scale apple orchards when fitted with traditional ATR nozzles rather than with air-induced TVI nozzles.

1. Introduction

The axial fan air-assisted sprayer fitted with hydraulic hollow cone nozzles is the predominant design of sprayers used in orchards. It produces a large radial spray plume, which could involve a significant risk of off-target contamination by spray drift and losses on the ground, a subject of increasing public concern. Several authors have reported losses in excess of 50% of the spray applied by axial fan sprayers (Cross et al., 2001). In apple orchards, spray losses on the ground can range from less than 2–39% of the total amount applied, and drift losses can account for 23–45%, depending mainly on leaf development and weather conditions (Vercruysse et al., 1999).

Other sprayer designs have been developed, including over-the-row tunnel spray systems. Although various studies have reported substantial savings in pesticides and a reduction in drift resulting from various types of tunnel spray systems (Peterson and Hogmire, 1995; Porskamp et al., 1994; Doruchowski and Holownicki, 2000; Planas et al., 2002; Ade et al., 2007), these sprayers are used only to

---

* Corresponding author. Tel.: +32 81620329; fax: +32 81620349.
E-mail addresses: jamar@cra.wallonie.be (L. Jamar), mostade@cra.wallonie.be (O. Mostade).

0261-2194/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cropro.2009.12.018

a limited extent because of increased cost and reduced operational flexibility. In addition, few studies have looked at the spray distribution on the canopy and spray lost on the ground from a modern tunnel sprayer compared with a standard fan sprayer. The uniformity of deposition has been reported, in some cases, to be less satisfactory than that from conventional axial-fan sprayers (Porskamp et al., 1994; Planas et al., 2002). It has proved difficult to design a tunnel sprayer that distributes spray uniformly on the trees and significantly reduces losses on the ground (Molari et al., 2005). In general, the results from non-conventional orchard spray technologies are still debatable because little information is available, and what there is tends to be controversial.

Apart from environmental concerns, another benefit of tunnel sprayers would be to reduce plot size in treatment trials using complex experimental designs following the EPPO guidelines. In order to conduct reliable evaluation trials using the tunnel sprayers, more information is needed about the spray distributions on the tree canopy.

A new promising option for drift mitigation in orchards could be the use of air induction cone nozzles, which provide larger drop sizes. Coarser droplets reduce the air-borne drift losses by mixing less readily with the surrounding atmospheric boundary layer (Walklate, 1992; McArtney and Obermiller, 2008). Spray distribution can be improved, however, by applying greater numbers of finer droplets which are more easily carried by the forced airflow of the sprayer (Cross et al., 2001; Derksen et al., 2007). Finer droplets with a smaller diameter give a greater coverage for any given level of spray deposit. The net result of these counteracting effects has been investigated only to a limited extent in orchards. According to Cross et al. (2001), the coarse sprays produced slightly greater mean deposits and smaller spray losses, and were preferable from this point of view. Further work is needed to establish the effect of biological efficacy of these spray patterns, although it has been shown that the effectiveness of insecticides is inversely proportional to drop size, and the limited data for fungicides suggest similar conclusions (Chapple et al., 1997; McArtney and Obermiller, 2008).

The objectives of this study were to assess the tunnel sprayer and the drift-mitigating nozzle performances compared with reference treatments using standard technologies. The amount and macro-distribution of spray deposits on the canopy, together with spray losses on the ground (sedimentation drift), were measured in a modern apple orchard system in two experiments. In a third set of experiments, the recycling rate obtained with the tunnel sprayer was assessed.

2. Materials and methods

2.1. Orchard and equipment

The study was conducted in an experimental dwarf apple orchard (cv. 'Pinova') planted in 2002 in Gembloux, Belgium (Jamar et al., 2008). Inter-row spacing was 3.5 m and intra-row spacing was 1.5 m. Orchard maintenance included a classical spindle shape training system. In 2008, the trees reached an average of 3.25 m high and 2.1 m wide.

Applications were performed with a standard axial fan air-assisted sprayer (Arbo AX 1000, Berthoud Agricole, 69 220 Belleville sur Saône, France) and a recycling tunnel sprayer (Type 115, Munckhof, 5961 CV Horst, The Netherlands), including the so-called 'Closed Loop System Technology'. Both sprayers were fitted with two sets of six nozzles. For the air assistance system of the standard sprayer, the fan rotational speed was 1600 rpm (low gear position). With the air assistance system of the tunnel sprayer, the air is sucked from inside the tunnel, producing an under-pressure area which helps eliminate most of the forward or backward spray drift. Air-borne droplets are partly intercepted by the tunnel's special design features and partly sucked back in by six axial-flow fans for subsequent re-use. The recovered spray is sucked in at the bottom of the collector walls using a Venturi system and transported to the sprayer tank after filtering. The internal opening of the tunnel was set at 2.40 m wide for all experiments, so the distance between the nozzles and the centre of the row was kept constant at about 1.2 m. The air outlets were angled at 45° upwards. For each sprayer, two types of spray nozzle were tried: the classical hollow cone nozzle (yellow Albuz ATR 80) and the air induction cone nozzle (green Albuz TVI 80-015) manufactured by Céramique Techniques Desmarquest from Evreux in France. For all the experiments, the power take-off (PTO) speed was fixed at 560 rpm, with a travel speed of 6.6 km h^{-1}. The working pressures were held in position at 10.5 and 12 bars for the ATR and TVI nozzles, respectively (Table 1).

During each experiment, air temperature, relative humidity, wind velocity and wind direction were recorded within the orchard at 3.5 m above the ground, using an iMETOS® AG IMT300 weather recorder (Pessl Instruments GmbH., 8160 Weiz, Austria, 2007). The local weather conditions were electronically monitored at the time of each spray application.

2.2. Treatments

The experiment involved four treatments: (i) standard sprayer with ATR nozzles, (ii) standard sprayer with TVI nozzles, (iii) tunnel sprayer with ATR nozzles and (iv) tunnel sprayer with TVI nozzles. In order to avoid external sources of variability, all the working parameters were kept as constant as possible in all treatments. The sprayers were calibrated to apply a constant rate of 350 l ha^{-1}. The spray liquid consisted of a mixture of 2 g l^{-1} of the water-soluble dye (fluorescein-sodium tracer, C.I. 45 350, Merck, Germany) in water for the canopy distribution experiment and 9 g l^{-1} for the sedimentation drift experiment. A sample tank liquid was taken immediately before and after completing each spraying to determine the exact concentration of the tracer in the spray tank.

2.3. Spray deposits in the canopy

The first experiment was carried out at full-leaf development stage during summer 2008 and was repeated four times, on 25 July, 1 August, and 2 and 10 September under varying weather conditions. For each treatment, four sampling repetitions in space were carried out, obtaining a completely randomized experimental design. Four

Table 1
Treatments.

Treatment	1	2	3	4
Sprayer	Standard	Standard	Tunnel	Tunnel
Nozzle trademark and type[a]	Albuz ATR	Albuz TVI	Albuz ATR	Albuz TVI
Size	Yellow	Green	Yellow	Green
Number of nozzles	12	12	12	12
Pressure (bar)	10.5	12	10.5	12
Measured spray liq. flow rate (l min^{-1})	1.12	1.12	1.12	1.12
Forward speed (km h^{-1})	6.6	6.6	6.6	6.6
Spray volume[b] (l ha^{-1})	350	350	350	350
Volume median diameter VMD (μm)[c]	78	507	78	507
PTO speed (rpm)	560	560	560	560

[a] ATR = ceramic hollow cone nozzle, TVI = air induction cone nozzle.

[b] Calculation based on 2857 m per ha.

[c] D50 values at 10 bars measured by the Cemagref on Dantec calibration.

blocks were established in a 150 m-long × 100 m-wide orchard section. The blocks, each consisting of part of six 36 m-long rows, were separated from each other by 10 m. In each block a central row 36 m long was sprayed from both sides, following the normal procedure for applying plant protection products in orchards. In every sprayed row, a one-tree sample was established in which an artificial target composed of 20 absorbent cellulose papers (Whatman, 1004110, 110 mm ø, Schleicher & Schuell) and 20 water-sensitive papers (26 × 76 mm, 20301-1N, Teejet Spraying Systems Co) were fixed on a specific metallic structure inserted in the foliage in order to evaluate the spray distribution on similar target positions for each treatment (Fig. 1). For each tree sample, the trees were divided into four zones according to their height (W: 0.0–0.20 m, X: 0.80–1.00 m; Y: 1.8–2.00 m; Z: 2.80–3.00 m) and into five zones according to their depth within the crop (I: external left, II: external right; III: central; IV: central left and V: central right).

In order to assess the relative deposit in the canopy (μg cm^{-2}) from each of the 20 sampling positions, the absorbent paper was collected immediately after spraying and put into a 125 ml plastic container and stored in a dark cool box in the field. In the laboratory the samples were cut into small square pieces (approx. 2 × 2 cm). The fluorescent dye was extracted by soaking and agitating each filter paper for 15 min in a constant volume of 0.5 l distilled water. The concentration of the dye tracer in the extraction water solution was determined using a UV-2101PC Shimadzu spectrophotometer working at a maximum absorbance wavelength of 492 nm, and the quantification was performed using the external standard calibration.

Water-sensitive papers were used to quantify the relative percentage spray cover, the number of droplets per cm^2 and the average droplet diameters resulting from the different spray techniques. The papers were clipped to a vertical wire-mesh support, matching the same 20 sampling positions in the canopy described earlier. The images of each water-sensitive paper were digitised using a Fujifilm FinePix S1Pro (6 million pixels SuperCCD, 1 pixel = 66 μm) and stored on a PC. The percentage spray cover, the number of droplets per cm^2 and the average droplet diameters on each water-sensitive paper were estimated by image analysis using Image-Pro Plus software version 6.1 (MediaCybernetics, East-West Hwy, USA).

2.4. Sedimentation drift

A second experiment, including the same four treatments described earlier, was performed to determine the spray losses on the ground on the downwind side of the experimental apple orchard with one boundary-row application. Four plots, separated from each other by 10 m, were established on a boundary row in a 150 m-long × 100 m-wide orchard section. The plots, each consisting of 36 m-long rows, were sprayed from both sides following the normal procedure for applying treatments in orchards. One sample location was established in each plot. A sample location consisted of eight cellulose collectors (110 mm ø large) placed on metallic boards on the ground and six cellulose strip collectors in the target space (an open space, free of vegetation) in the row up to 3.2 m high. The ground collectors were placed outside the orchard up to 10.5 m at a right angle to the rows. For the four treatments, four sampling repetitions in space were carried out based on a fully randomized experimental design and the experiment was repeated three times on 25 July, 1 August and 2 September 2008 under varying weather conditions. The procedure described above was used to collect and assess spray deposits from cellulose papers in the laboratory.

2.5. Spray recycling

A third experiment was performed to assess the recycling spray rate of the tunnel sprayer. In the same orchard as the one described in 2.1 (a 7-year-old apple orchard), the experiment consisted of spraying 0.5 ha with water at a spray rate of 350 l ha^{-1} and to assess the spray mixture recycling rate. Both the applied and recycled volumes were easily measured because the experimental tunnel sprayer was fitted with an individual tank receiving the recycled mixture. The experiment was repeated three times before flowering and three times after flowering, using either ATR or TVI nozzles as described earlier. The working speed of the sprayer was 6.6 km h^{-1}. The working pressure was 10.5 bars for ATR nozzles and 12 bars for TVI nozzles in order to obtain the same flow rate for both nozzles.

2.6. Data analysis

The measured deposits were normalized for differences in dye concentration in the spray mixture. Before statistical analyses, transformation of the variables had been applied to reflect normality and variance equality. For spray deposits (μg cm^{-2}) and average droplet diameters (μm), the log transformation was applied, and for the spray cover (%) and the number of droplets per cm^2 the angular and square root transformations, respectively, were carried out. All data analyses were performed using SAS software version 9.1 (SAS Institute, Cary, North Carolina, USA). The Student-Newman-Keuls multiple range tests, with a 95% confidence level, were performed to investigate the differences between the deposition levels obtained with the tested sprayers and nozzles.

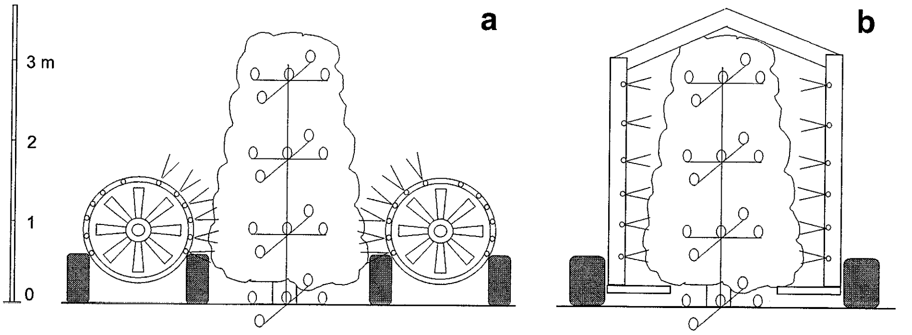

Fig. 1. Schematic representation of one-tree sample including 20 artificial collectors used in the spray deposit experiment, in relation with the nozzle positions of the standard sprayer (a) and the tunnel sprayer (b).

3. Results and discussion

3.1. Spray deposits in the canopy

All the treatments were conducted under constant climatic conditions and very low wind speeds (below 2 m s^{-1}), which therefore did not have any significant influence on the results.

The first experiment showed that for the classical hollow cone nozzle (ATR), the application with the tunnel sprayer produced an amount of spray deposit comparable with the standard sprayer at each level of the canopy (Table 2). With regard to the air induction nozzle (TVI), the tunnel sprayer produced a significantly lower spray deposit in the treetop than the standard sprayer. The greater spray deposit was obtained with the standard sprayer combined with the TVI nozzles, but this modality of treatments included a lower spray cover than the ATR nozzle option. For both sprayers and both nozzles, notably lower spray deposits and spray covers were registered in the high part of the tree compared with the middle and low parts of the tree, but these differences were much more pronounced with the combination of the TVI nozzles and the tunnel sprayer. In addition, compared with the standard sprayer, the tunnel sprayer produced significantly greater deposits on sampling beneath the row of trees, whatever the nozzle types. With the TVI nozzle, the tunnel sprayer greatly increased the deposit beneath the row of trees compared with the standard sprayer (Table 2). This suggests that the air-assistance design of the tunnel sprayer used should be adapted to the kind of nozzle and the orchard structure. It seems that the design of the tunnel sprayer tested was not well adapted to trees that were 3.25 m high, but was better adapted to smaller trees. Previous studies have demonstrated that the tunnel sprayers performed better than conventional sprayers on dwarf trees 2.7 m high, in terms of in-canopy spray deposit (Peterson and Hogmire, 1995; Hogmire and Peterson, 1997; Holownicki et al., 1997a), leaf coverage or distribution uniformity (Cross and Berrie, 1993; Holownicki et al., 1997a). Others studies have reported that the uniformity of the canopy spray deposition was worse than that obtained with the axial-flow sprayer in a 2.80 m high apple orchard (Planas et al. 2002) and in a 3.25 m-high apple orchard (Mostade et al., 2008). The authors attributed this to poor adjustment of the tunnel to the crop size or to inadequate air-jet design. In medium-sized trees, however, the tunnel sprayer provided a similar level of apple scab or powdery mildew control (Cross and Berrie, 1993; Holownicki et al., 1997b; Panneton et al., 2001) compared with the standard sprayer. In addition, apple scab control was provided by a low annual amount of active ingredient using a tunnel sprayer for treatment applications in 5- and 6-year-old apple orchards 3 m-high composed of high scab-susceptible cultivars (Jamar et al., 2008).

The percentage of spray cover was significantly higher with the standard sprayer than with the tunnel sprayer, for both nozzles (Table 2). The stain diameter obtained with the tunnel sprayer for either nozzle was greater and the number of stains was fewer compared with the standard sprayer. As shown by Sierra et al. (2006), Derksen et al. (2007) and McArtney and Obermiller (2008),

Table 2
Distribution of normalized spray deposits on artificial targets positioned beneath the tree canopy and in different sampling zones of the tree canopy.

Nozzle	Sprayer	Beneath the tree canopy	Inside the tree canopy[a]			
		Zone W	Zone X	Zone Y	Zone Z	Mean X,Y,Z
Spray deposit (μg cm^{-2})[b]						
ATR	Standard	0.33 a[c]	0.79 ab	0.70 a	0.50 b	0.66 a
	Tunnel	0.61 b	0.77 a	0.84 ab	0.46 ba	0.69 a
TVI	Standard	0.37 a	1.03 c	0.94 b	0.79 c	0.92 b
	Tunnel	1.48 c	0.98 bc	0.82 ab	0.36 a	0.72 a
P-value		***	**	*	***	***
Spray cover (%)						
ATR	Standard	18.1 a	46.9 b	51.2 c	36.5 c	44.9 c
	Tunnel	32.2 b	36.8 ab	45.6 cb	19.7 b	34.1 b
TVI	Standard	13.5 a	35.4 ab	35.9 b	29.8 c	33.7 b
	Tunnel	47.1 c	24.8 a	23.9 a	7.4 a	18.7 a
P-value		***	**	***	***	***
Number of stains per cm^2						
ATR	Standard	294 d	231 c	227 d	273 d	244 d
	Tunnel	203 c	195 c	193 c	225 c	204 c
TVI	Standard	57 a	107 b	90 b	95 b	97 b
	Tunnel	79 b	60 a	69 a	47 a	59 a
P-value		***	***	***	***	***
Average stain diameters (μm)						
ATR	Standard	187 a	189 a	179 a	173 a	180 a
	Tunnel	213 a	199 a	189 a	180 a	190 a
TVI	Standard	335 b	260 b	279 b	290 b	277 b
	Tunnel	312 b	410 c	364 c	409 c	395 c
P-value		***	***	***	***	***

* Significant at $P \leq 0.05$; ** Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$.
Because of the back-transformation of the variable data sets, no SED (Standard errors of differences) values are available.

[a] Sampling zones according to height (zone W: from 0.0 to 0.2 m; zone X: from 0.8 to 1.0 m; zone Y: from 1.8 to 2.0 m; zone Z: from 2.8 to 3.0 m).

[b] Normalized fluorescein concentration in the sprayers was 1177.6 μg ml^{-1}.

[c] In each experiment, values within columns followed by different letters are significantly different according to the Student-Newman-Keuls multiple range tests.

several factors, including carrier rate, turbulence and formulation as well as droplet size, can affect spray coverage. The number of stains per cm^2 was significantly lower with the TVI, in line with increased stain diameters. In most cases, the TVI nozzles provided significantly higher spray deposits and lower spray cover in the canopy than the ATR nozzles, for both sprayers. There was evidence of an inverse relationship between spray cover rate and average droplet diameter, and a direct relationship between spray cover and number of droplets per cm^2. If differences in the micro- and macro-distribution occur with nozzle types, the consequences for biological effectiveness need to be determined. For some pesticides, at least theoretically, a coarser pattern of spray deposition on the leaf surface could be less effective biologically. Further investigation of the effects of spray quality adjustment on biological effectiveness is required. According to Allen et al. (1978), finer sprays are considerably more effective. Such sprays would therefore be preferable because the dose rate could be reduced, although finer sprays could lead to greater air-borne drift and spray losses.

In most cases, a slightly lower spray deposit was registered in the centre of the canopy compared with the external part of the canopy for both sprayers and nozzles (Table 3), but these differences were not significant. This means that a relatively good degree of penetration was obtained with all modalities of treatments.

3.2. Sedimentation drift

In the second experiment, the overall mean of the sedimentation drift was similar for all treatments, whatever the sprayer or nozzle. For all treatments, the average sedimentation drifts ranged from 5.8 to 9.1% of the total amount of the tracer sprayed (Table 4). This finding seems to be linked to the high canopy density at the full-leaf development stage, the high tree row volume value and the low wind speeds. Accordingly to Vercruysse et al. (1999) and Cross et al. (2001), spray losses on the ground are generally greatest in small tree orchards with poor foliage densities, and lowest in the large tree orchards with full foliage development.

The sedimentation drift distribution, however, was quite different depending on the sprayers and the nozzles. In comparison with the standard sprayer, the tunnel sprayer produced significantly greater sedimentation drift on the ground samplings beneath the row of trees and smaller sedimentation drift on the ground samplings downwind of the sprayer (2.5–10.5 m from the treated row of trees) (Table 4). Therefore, spray losses on the ground measured during the tunnel sprayer applications were restricted mainly to beneath the crop rows, confirming previous findings (Porskamp et al., 1994; Doruchowski and Holownicki, 2000; Planas et al., 2002). With the TVI nozzle, the tunnel sprayer greatly increased the sedimentation drift beneath the row of trees compared with the standard sprayer (Table 4). By contrast, with the standard sprayer the sedimentation drift beneath the tree rows was not significantly influenced by nozzle type. This suggests that the airflow characteristics of the tunnel sprayer are not well adapted to coarse droplet size spectrums, composed of heavier drops. New simulative methods have been developed to forecast appropriate air fluxes at the design stage. For example, Molari et al. (2005), use 'computational fluid dynamics' studies for checking sprayer performance and building an improved prototype of recycling tunnel sprayers with reduced losses on the ground and improved spray distribution on the canopy.

Table 3
Distribution of normalized spray deposits in the centre and on the external part of the canopy.

Nozzle	Sprayer	Spray deposit (μg cm^{-2})[a]			Spray cover (%)		
		Centre	Extern	Ratio C/E	Centre	Extern	Ratio C/E
ATR	Standard	0.56 a[b]	0.69 ab	0.81	34.3 dc	47.5 d	0.72
	Tunnel	0.56 a	0.72 ab	0.77	28.4 bc	35.5 dc	0.80
TVI	Standard	0.87 b	0.93 b	0.94	29.0 bc	34.8 dc	0.83
	Tunnel	0.60 a	0.75 ab	0.80	14.3 a	19.8 ab	0.72
P-value		***			***		

*** Significant at $P \leq 0.001$.

[a] Normalized fluorescein concentration in the sprayers was 1177.6 μg ml^{-1}.

[b] In each experiment, values followed by different letters are significantly different according to the Student-Newman-Keuls multiple range tests.

Table 4
Normalized sedimentation drift.

Mean sedimentation drift (μg cm^{-2})[a, b]

Nozzle	Sprayer	Distance from the treated row of trees (m)						
		0.0	*1.25*	*2.5*	*4.5*	*6.5*	*8.5*	*10.5*
ATR	Standard	0.64 a[c]	0.62 a	0.46 b	0.38 b	0.28 b	0.19 a	0.15 a
	Tunnel	1.60 b	1.07 a	0.33 a	0.16 a	0.16 a	0.13 a	0.13 a
TVI	Standard	0.69 a	0.91 a	0.95 c	0.69 b	0.45 b	0.17 a	0.16 a
	Tunnel	4.40 c	0.88 a	0.18 a	0.14 a	0.14 a	0.14 a	0.14 a
P-value		***	ns	***	***	***	ns	ns

Weighted mean sedimentation drift (μg cm^{-2})

Nozzle	Sprayer	Space from the treated row of trees (m)		
		0–2.5	2.5–10.5	0–10.5
ATR	Standard	0.59 a	0.29 b	0.36 a
	Tunnel	1.02 b	0.17 a	0.37 a
TVI	Standard	0.80 a	0.47 c	0.56 a
	Tunnel	1.59 c	0.15 a	0.48 a
P-value		**	**	ns

ns: nonsignificant, **: significant at $P \leq 0.01$, ***: significant at $P \leq 0.001$.

[a] Normalized fluorescein concentration in the sprayers was 5285.8 μg ml^{-1}.

[b] Mean target space (free of vegetation) deposits were not significantly different among treatments and the average value was 3.14 μg cm^{-2}.

[c] Values within columns followed by different letters are significantly different according to the Student-Newman-Keuls multiple range tests.

In contrast, for the application with the standard sprayer, the sedimentation drifts were significantly greater on sampling downwind of the sprayer compared with the tunnel sprayer. The TVI treatments increased the ground deposit downwind of the sprayer compared with the ATR treatments (Table 4). If there are differences in sedimentation drifts, the correlation with air-borne drift needs to be determined. In our experiments only the spray losses on the ground were evaluated, although during spray applications the spray that was discharged and not deposited on the canopy was lost either to the ground as fallout or to the air as air-borne drift. Cross et al. (2001) reported that the fine spray qualities resulted in more spray being lost as air-borne drift than with coarser spray, although the differences were not always significant.

3.3. Spray recycling

For the spray recycling experiment, the weather conditions at each assessment date are shown in Table 5. The recovery system, which included a continuous recycling process in the tunnel sprayer, led to an average of 30% being saved from the applied spray mixtures when spraying under moderate wind speed (≤ 2.5 m s^{-1}) in a 7-year-old apple orchard (Table 5). The level of spray saved depended greatly on the tree growth stages. The measured spray savings due to the recycling system varied from 22 to 38%, depending on leaf development stage and nozzle type, which accords with previous

Table 5
Recycling rate achieved with the tunnel sprayer using ATR and TVI nozzles during the 2008 season, in a 7-year-old apple orchard (applied volume was 350 l ha^{-1}).

Date	GS[a]	T[b]	RH[b]	Wind speed	Wind direction[b]	Recycled rate	
						ATR	TVI
		°C	%	m s^{-1}	°	%	%
10 April	D	13	60	2.1	75	36	38
18 April	E	15	55	1.6	89	35	36
25 April	F	12	58	2.4	55	31	35
16 May	H	15	74	1.9	120	24	32
13 June	I	17	71	1.6	102	23	26
04 July	J	18	68	2.3	42	22	24

[a] GS = Tree growth stages according to the Fleckinger-growth stage scale (F = full bloom).

[b] T = temperature, RH = relative humidity; Wind direction in relation to the sprayer track.

studies using various tunnel sprayer designs (Cross and Berrie, 1993; Holownicki et al., 1997b). It has been found that the recycling rate increases with higher spray volume rates and with decreasing driving speed and size of trees, and many researchers have reported a decrease in the recycling rate as the season progressed, following the leaf development stage (Doruchowski and Holownicki, 2000).

4. Conclusions

This study showed that, under low wind speed, in comparison with the standard axial fan sprayer, the tunnel sprayer produced an equivalent spray deposit in all areas of the trees showing comparable vertical and horizontal macro-distribution uniformity, with the hydraulic hollow cone (ATR) nozzles, a nozzle that produces small droplets. With the air induction (TVI) nozzles, however, a nozzle that produces large droplets, the tunnel sprayer produced a significantly lower spray deposit and a lower spray cover, especially in the top of the canopy, compared with the standard sprayer. At the same spray deposit level, the tunnel sprayer provided relatively lower spray cover on the canopy than the standard sprayer, whatever the nozzle type. At the same spray deposit level, the ATR nozzles provided significantly greater spray cover on the canopy than the TVI nozzles for both sprayers. The greatest spray deposit was obtained with the combination 'standard sprayer - TVI nozzles', although the spray cover rate was not the highest in this case.

The average sedimentation drifts ranged from 5.8 to 9.1% of the total amount of the tracer sprayed, whatever the sprayer or nozzle. In comparison with the standard sprayers, the tunnel sprayer produced a statistically comparable overall mean sedimentation drift, although the distribution of the sedimentation drift was quite different between the two sprayers. The tunnel sprayer limits the sedimentation drift beneath the tree rows and could, therefore, be used successfully in experimental design with reduced plot sizes. The TVI nozzles did not significantly improve the overall ground losses compared with the ATR nozzles, for both sprayers.

The spray mixture recycling rate in the tunnel sprayer varied from 38 to 22% over the growing season, showing high environmental sustainability compared with traditional machines.

These experiments indicate that the tunnel sprayer could be suitable for use with traditional hydraulic nozzles (ATR), but not with the air-induced nozzle (TVI), to make applications on dwarf apple orchards up to 2.8 m high. The tunnel sprayer should be adapted to improve the performances and the spray distributions on the treetop, particularly in the presence of higher trees and drift-mitigating nozzles producing coarser droplets. Further studies are needed to clarify (i) differences in biological effectiveness between tunnel and standard sprayers and (ii) differences in-canopy distribution and ground losses under higher wind speeds and less favourable climatic situations.

Acknowledgements

This research is funded by the Ministry of the Walloon Regional Government, General Department of Agriculture, Research Direction, project RW D31-1105. The authors would like to thank Drs R. Oger and V. Planchon (CRA-W, Gembloux) for their important help in the statistical analysis, and S. Pekel and G. Dubois (CRA-W) for their useful co-operation in this research.

References

Ade, G., Molari, G., Rondelli, V., 2007. Recycling tunnel sprayer for pesticide dose adjustment to the crop environment. Trans. ASAE 50, 409–413.

Allen, J.G., Butt, D.J., Dicker, G.H.L., Hunter, L.D., 1978. A comparison of the efficiency of sprays of two drop-size ranges in an apple orchard. Pestic. Sci. 9, 545–554.

Chapple, A.C., Wolf, T.M., Downer, R.A., Taylor, R.A.J., Hall, F.R., 1997. Use of nozzle-induced air-entrainment to reduce active ingredient requirements for pest control. Crop Prot. 16, 323–330.

Cross, J.V., Berrie, A.M., 1993. Spray deposit and efficacy of a tunnel sprayer at three volume rates (50, 100, 200 l/ha) in comparison with an axial fan (50/ha) sprayer on apple. Proc. Second Int. Symp. Pestic. Appl. Tech. 1/2, 273–280. ANPP Ann.

Cross, J.V., Walklate, P.J., Murray, R.A., Richardson, G.M., 2001. Spray deposits and losses in different sized apple trees from an axial fan sprayer: 2. Effect of spray quality. Crop Prot. 20, 333–343.

Derksen, R.C., Zhu, H., Fox, R.D., Brazee, R.D., Krause, C.R., 2007. Coverage and drift produced by air induction and conventional hydraulic nozzles used for orchard applications. Trans. ASAE 50, 1493–1501.

Doruchowski, G., Holownicki, R., 2000. Environmentally friendly spray techniques for tree crops. Crop Prot. 19, 617–622.

Hogmire, H.W., Peterson, D.L., 1997. Pest control on dwarf apples with a tunnel sprayer. Crop Prot. 16, 365–369.

Holownicki, R., Doruchowski, G., Swiechowski, W., 1997a. Uniformity of spray deposit within apple tree canopy as affected by direction of the air-jet in tunnel sprayers. J. Fruit Ornamental Plant Res. 5, 129–136.

Holownicki, R., Doruchowski, G., Godyn, A., Swiechowski, W., 1997b. Minimising pesticide waste and emission to the environment by using tunnel sprayers. J. Fruit Ornamental Plant Res. 5, 137–144.

Jamar, L., Lefrancq, B., Fassotte, C., Lateur, M., 2008. A during-infection spray strategy using sulphur compounds, copper, silicon and a new formulation of potassium bicarbonate for primary scab control in organic apple production. Eur. J. Plant Pathol. 122, 481–492.

McArtney, S.J., Obermiller, J.D., 2008. Comparative performance of air-induction and conventional nozzles on an axial fan sprayer in medium density apple orchards. Horttechnology 18, 365–371.

Molari, G., Benini, L., Ade, G., 2005. Design of a recycling tunnel sprayer using CFD simulations. Trans. ASAE 48, 463–468.

Mostade, O., Jamar, L., Huyghebaert, B., Miserque, O., Pigeon, O., 2008. Quality of spraying in apple orchard. Proceeding of 10th International Congress on Mechanization and Energy in Agriculture. 14-17th octobre. Antalya-Turquie, 308–313.

Panneton, B., Theriault, R., Lacasse, B., 2001. Efficacy evaluation of a new spray-recovery sprayer for orchards. Trans. ASAE 44, 473–479.

Peterson, D.L., Hogmire, H.W., 1995. Evaluation of tunnel sprayer systems for dwarf fruit trees. Appl. Eng. Agric. 11, 817–821.

Planas, S., Solanelles, F., Fillat, A., 2002. Assessment of recycling tunnel sprayers in Mediterranean vineyards and apple orchards. Biosystem Eng. 82, 45–52.

Porskamp, H.A., Michielsen, J.M., Huijsmans, J.F., 1994. Emission-Reducing Pesticide Applications in Fruit Growing. Research Deposition and Emission of Pesticides. IMAG-DLO Report 94-19, IMAG-DLO, Wageningen, 43 pp.

Sierra, J.G., Ortiz-Canavate, J., Sanhueza, J.R., 2006. Short communication. Performance of pneumatic spraying with an over-the-row sprayer in high density apple tree orchards. Spanish J. Agric. Res. 4, 26–30.

Vercruysse, F., Steurbaut, W., Drieghe, S., Dejonckheere, W., 1999. Off target ground deposits from spraying a semi-dwarf orchard. Crop Prot. 18, 565–570.

Walklate, P.J., 1992. A simulation study of pesticides drift from an air-assisted orchard sprayer. J. Agric. Eng. Res. 51, 263–283.