果 树 学 报 2024,41(9):1821-1828
Journal of Fruit Science

DOI:10.13925/j.cnki.gsxb.20240110

果园风送式喷雾机在现代矮砧苹果园的喷施效果评价

朱力争[1],王 涛[2],王 丹[2],余贤美[2],翟 浩[2*]

([1]山东省费县果茶服务中心,山东费县 273400;[2]山东省果树研究所,山东泰安 271000)

摘 要:【目的】探究风送式塔型喷雾机在矮砧宽行密植苹果园中的施药效果,优化施药参数,为现代矮砧苹果园农药施用"减量增效"提供理论参考。**【方法】**以5年生烟富3苹果为试验材料,采用水敏纸雾滴测试卡测定3WF-1000风送式塔型喷雾机雾滴粒径、雾滴密度与覆盖率,并利用示踪剂诱惑红测定喷雾机的药液沉积量及地面沉积量。**【结果】**在5年生现代矮砧宽行密植苹果园中,喷雾机在不同牵引速度下的雾滴特性差异显著,与牵引速度为1.16 m·s^{-1}(4.18 km·h^{-1})时相比,牵引速度为1.77 m·s^{-1}(6.37 km·h^{-1})时的雾滴覆盖率和雾滴粒径由62.19%和142.67 μm下降到57.03%和131.67 μm,而雾滴密度由141.72点•cm^{-2}增加到179.86点•cm^{-2};牵引速度为1.77 m·s^{-1}时的叶面平均沉积量、地面沉积量和农药利用率分别为0.24 μg·cm^{-2}、0.55 μg·cm^{-2}和47.1%,均高于1.16 m·s^{-1}时(分别为0.22 μg·cm^{-2}、0.43 μg·cm^{-2}和43.7%)。**【结论】**3WF-1000型风送式喷雾机两个牵引速度(1.16 m·s^{-1}和1.77 m·s^{-1})的雾滴特性均能满足矮砧宽行密植苹果园病虫害的防治要求,喷雾机在牵引速度1.77 m·s^{-1}时农药利用率更高,但易导致土壤流失率增高。

关键词:果园;风送式喷雾机;雾滴密度;雾滴覆盖率;雾滴粒径;利用率;流失率

中图分类号:S661.1　　**文献标志码:**A　　**文章编号:**1009-9980(2024)09-1821-08

Evaluation of spraying efficacy of the air-assisted orchard sprayer in modern dwarfing-rootstock apple orchard

ZHU Lizheng[1], WANG Tao[2], WANG Dan[2], YU Xianmei[2], ZHAI Hao[2*]

([1]Feixian Fruit Tea Service in Shandong Province, Feixian 273400, Shandong, China; [2]Shandong Institute of Pomology, Tai'an 271000, Shandong, China)

Abstract:【Objective】Combining good application technology with advanced application machinery, optimizing parameters such as droplet size, spray volume and traction speed can give full play to the performance of application instruments, improve the utilization rate of pesticides, and achieve precise prevention and control. However, the normative evaluation of the application efficacy of modern machinery, and the reference of the measure adjustment and the equipment improvement are lacking. This research aimed to investigate the spraying effect of air-assisted sprayer, optimize application parameters by comparing and analyzing the changes of droplet characteristics, droplet deposition distribution and ground loss rate of 3WF-1000 air-assisted tower sprayer in the apple orchard with wide planting rows and dwarfing rootstocks, so as to provide theoretical reference for pesticide application "reducing quantity and increasing efficiency" in modern dwarfing-rootstock apple orchards.【Methods】Five-year-old Yanfu 3 apple cultivar with spindle-shaped canopy was used as experimental material. The spacing between plants and rows were (1.25−1.50) m × 4.5 m, respectively. The volume median diameter (VMD), droplet density and droplet coverage of the 3WF-1000 air-assisted tower sprayer were tested by water-

收稿日期:2024-03-11　　**接受日期:**2024-07-17

基金项目:国家现代农业产业技术体系(CARS-27);山东省重点研发计划(2017CXGC0214)

作者简介:朱力争,男,高级农艺师,主要从事果茶新品种引进、新技术推广、果茶技术培训和指导等相关工作。E-mail:zhuli72zheng@163.com

*通信作者 Author for correspondence. E-mail:zhaihao688@163.com

sensitive paper, and the foliar deposition and ground deposition were tested by tracer agent allura red. A row with the length of 50 m was selected as the test plot and three discontinuous apple trees were randomly selected as sampling points. In order to investigate the droplet characteristics, the canopy was vertically divided into upper (2.0 m), middle (1.5 m) and lower (1.0 m) layers, and five points were selected as distribution sample points in the east, south, west, north and middle of each canopy. A paper clip was used to fix each water-sensitive paper with the detection face down. To investigate the ground loss rate, a dish was placed in each of four directions (east, south, west and north), 30 cm away from the trunk. 20 g of allura red was fully dissolved in 100 L of water and added to the sprayer at the traction speeds of 1.16 $m \cdot s^{-1}$ (4.18 $km \cdot h^{-1}$) or 1.77 $m \cdot s^{-1}$ (6.37 $km \cdot h^{-1}$). The water-sensitive paper was put into a plastic bag and brought back to the laboratory. After scanning, the droplet size, droplet density and coverage were measured by Image J software. In order to test the foliar deposition, three leaves were collected at each sampling point. After measuring the leaf area, each leaf was washed with 5 mL distilled water for 10 min, the absorption of the washing solution at 501 nm was determined, and the concentration of allura red was calculated according to the standard curve. The dried dishes were added with 10 mL distilled water, and shaken at 100 $r \cdot min^{-1}$ for 5 min. The absorption of the washing solution at 501 nm was measured and the concentration of allura red was calculated. 【Results】The droplet characteristics of the sprayer at different traction speeds were significantly different in the five-year-old modern dwarfing-rootstock and wide-row apple orchard. Compared with the traction speed of 1.16 $m \cdot s^{-1}$ (4.18 $km \cdot h^{-1}$), the droplet coverage and VMD at 1.77 $m \cdot s^{-1}$ (6.37 $km \cdot h^{-1}$) decreased from 62.19% and 142.67 μm to 57.03% and 131.67 μm, and the droplet density (141.72 $points \cdot cm^{-2}$) increased to 179.86 $points \cdot cm^{-2}$. The average foliar deposition, ground deposition and utilization rate at the speed of 1.77 $m \cdot s^{-1}$ were 0.24 $\mu g \cdot cm^{-2}$, 0.55 $\mu g \cdot cm^{-2}$ and 47.1%, respectively, and were both higher than those of 1.16 $m \cdot s^{-1}$ (0.22 $\mu g \cdot cm^{-2}$, 0.43 $\mu g \cdot cm^{-2}$, and 43.7%, respectively). The droplet parameters of the sprayer in the east, south, west, north and middle of the tree were also different at two traction speeds. When the traction speed was 1.77 $m \cdot s^{-1}$, the droplet coverage in the east, west, south and north was lower than that at the traction speed of 1.16 $m \cdot s^{-1}$, but it was opposite in the middle canopy, which was significantly higher than that at the traction speed of 1.16 $m \cdot s^{-1}$ ($p<0.05$). The droplet particle size at the traction speed of 1.77 $m \cdot s^{-1}$ was lower than that at 1.16 $m \cdot s^{-1}$ in all 5 directions, and the south direction had a significant difference ($p<0.05$). The droplet density in the east, west, north and middle of the tree at the traction speed of 1.77 $m \cdot s^{-1}$ was higher than that at 1.16 $m \cdot s^{-1}$, while the droplet density in the south was slightly lower. The distribution of foliar deposition at the two traction speeds of the sprayer was in such a descending order: the upper canopy > the middle canopy ⩾ the lower canopy of the tree, and the deposition amount in the outer of the tree was higher than that in the inner at the height of the middle and low canopy. At the traction speed of 1.77 $m \cdot s^{-1}$, the deposition amount in the inner and outer canopy of the middle and lower canopy (deposition ratio of inner to outer was 0.73 and 0.65) was higher than that at the traction speed of 1.16 $m \cdot s^{-1}$ (deposition ratio of inner to outer was 0.72 and 0.64). However, there was no significant difference in the amount of liquid deposited in the upper, middle and lower canopy of the tree ($p<0.05$). 【Conclusion】The droplet characteristics of the 3WF-1000 air-assisted sprayer at two traction speeds (1.16 $m \cdot s^{-1}$ and 1.77 $m \cdot s^{-1}$) could meet the requirements of disease and pest control in modern dwarfing-rootstock apple orchards. The better pesticide utilization rate was observed with the sprayer at the traction speed of 1.77 $m \cdot s^{-1}$, but the soil loss rate would increase as well.

Key words: Orchard; Air-assisted sprayer; Droplet density; Droplet coverage; Volume median diameter (VMD); Utilization rate; Ground loss index

农药在控制农作物病虫草危害,保证农产品产量与质量等方面具有不可替代的作用。据统计,2018年中国农药使用量在30万t左右[1](折百量),但农药利用率仅为36.6%[2],农药流失浪费严重,对土壤、河流和地下水系造成严重污染[3],限制了农业的绿色可持续发展。果树作为多年生木本植物,生长周期长,病虫害种类繁杂及发生规律各异,且中国传统一家一户分散经营的果园种植模式无法实现病虫害的统防统治,落后的施药器械"跑、冒、滴、漏"现象严重,致使果园用药次数多,农药使用量大。为提升农产品附加值,促进农业绿色发展,农业部于2016年提出"农药化肥双减"和"农药零增长"[4]的概念和目标。其中,应用高效施药器械、提高农药利用率是果园农药减施的重要组成部分。

苹果现代矮砧集约栽培模式是中国苹果生产发展的主流方向,该模式"宽行、高干、集约、高效"的栽培特点,更适合应用大中型果园机械。随着现代矮砧集约栽培模式在中国苹果优势产区的迅速发展[5],风送式喷雾机由于具有工作强度低、安全性好、利用率高、防效高等优点,在矮砧集约栽培果园中广泛应用。但是,风送式喷雾机在果园的应用效果受诸多因素的影响,不同的农药剂型和助剂影响药液在靶标植物叶片上的附着[6-7];药械喷头对药液的流量、喷雾角度、雾滴大小等指标亦有较大影响[8-11];植株冠层结构、叶片表面特性和环境条件对果园农药利用率的影响也较大[12-14]。针对果园的立地条件和果树树体结构,专家学者对机械的各项指标进行调整,相继研发出果园自动对靶静电喷雾机[15]、自走履带式风送果园变量喷雾机[16]、自动仿形变量喷雾机[17]、自走式精准变量喷杆喷雾机[18]和植保无人机[19]等精准施药机械。将良好的施药技术与先进的施药机械相结合,调整优化雾滴粒径、喷雾量和牵引速度等各项参数,才能充分发挥施药器械性能,提高农药利用率,实现精准防控。但由于目前缺少对现代化施药机械施药效果的规范性评价,施药措施的调整与药械的改进缺少充足的参考。

笔者在本研究中通过对比分析不同牵引速度下3WF-1000风送式塔型喷雾机在5年生矮砧宽行密植苹果园中雾滴特性、雾滴沉积分布和地面流失率的变化,综合评价3WF-1000风送式塔型喷雾机在矮砧宽行密植苹果园中的施药效果,摸索并优化施药参数,以期为矮砧宽行密植苹果园中农药施用"减量增效"提供理论依据和数据支持。

1 材料和方法

1.1 材料

供试果园:山东省威海市大水泊镇矮砧宽行密植苹果园(37°11' N,122°15' E)。以5年生烟富3苹果为试验材料,纺锤形树冠,株行距(1.25~1.50 m)×4.50 m,南北走向,果园自然生草。

设备及试剂耗材:3WF-1000风送式塔型喷雾机(威海新元果业技术服务有限公司,容积1000 L,工作压力0.5~3.0 MPa,长×宽×高为3.20 m×1.40 m×2.26 m,设备额定转速540 $r\cdot min^{-1}$,流量135 $L\cdot min^{-1}$)。U-3900型紫外分光光度计(日立,日本);CI-202便携式激光叶面积仪(CID公司,美国);培养皿(直径7 cm);食品染色剂诱惑红(上海染料研究所),蒸馏水,水敏纸雾滴测试卡(中国农业科学院植物保护研究所生产)。

1.2 方法

1.2.1 诱惑红标准溶液配制及标准吸收曲线的测定 称取诱惑红0.01 g,将其溶解并转移至10 mL容量瓶中定容,配成质量浓度为1000 $\mu g\cdot mL^{-1}$的母液。分别用移液枪移取母液50、150、250、350、450、550、650 μL至7个10 mL容量瓶中定容,配制成5、15、25、35、45、55、65 $\mu g\cdot mL^{-1}$系列质量浓度的诱惑红溶液。用U-3900型紫外分光光度计测定上述标准溶液在501 nm波长下的吸光度,并绘制标准曲线。

1.2.2 雾滴特性、雾滴沉积分布和地面流失的测定 选择长50 m的一行果树作为试验小区,喷雾开始前,随机选取3株不连续苹果树进行采样点布置。为研究苹果树冠层的雾滴特性,在垂直方向将树冠层分为上、中、下3层(2.0 m、1.5 m和1.0 m),在冠层的东、南、西、北、中选五点作为布样点(图1)。用回形针分别固定一张检测面朝下的水敏纸雾滴测试卡。为研究雾滴的地面流失率,在距离树干30 cm处的4个方位(东、南、西、北)各放置一个培养皿(图2-A)。雾滴特性以各方位布样点的平均值表示。

将20 g诱惑红充分溶解于100 L水中,加入3WF-1000风送式塔型喷雾机,在牵引速度为1.16 $m\cdot s^{-1}$(4.18 $km\cdot h^{-1}$)和1.77 $m\cdot s^{-1}$(6.37 $km\cdot h^{-1}$)时对果树进行喷施,测量剩余溶液体积以确定用水量。将晾干的水敏纸放入塑封袋中,带回实验室,用扫描仪扫描后,用Image J软件测定分析覆盖率、雾滴粒径和雾

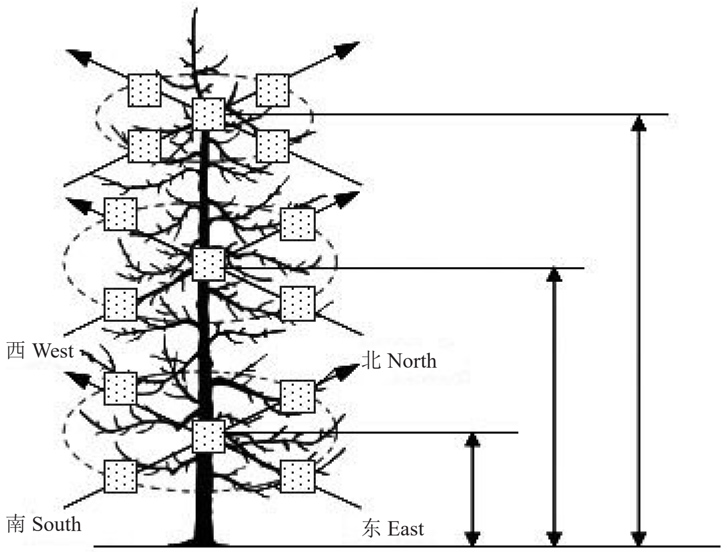

图1 水敏纸取样点分布

Fig. 1 Schematic diagram of water-sensitive paper sampling point

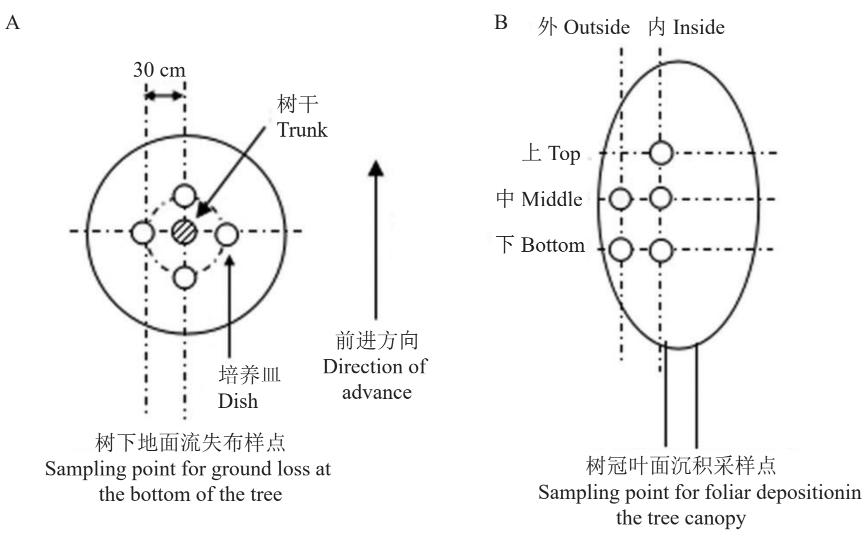

图2 雾滴沉积分布取样点

Fig. 2 Schematic diagram of droplet deposition distribution sampling point

滴密度；为研究苹果树冠层的药液沉积量，在每个采样点各采集3片叶（图2-B），在实验室中测定叶面积后，每片叶用5 mL蒸馏水振荡洗涤10 min，测定洗涤液在501 nm下的吸光值，根据标准曲线计算诱惑红浓度；将风干后的培养皿带回实验室，每个皿加入10 mL蒸馏水，100 r·min^{-1}震荡5 min，测定洗涤液在501 nm下的吸光值并计算诱惑红浓度。

1.2.3 数据计算与分析 按以下公式计算药液沉积量、利用率、地面沉积量和地面流失率[20-21]。用扫描仪扫描水敏纸，并用分析软件Image J测定分析雾滴密度、覆盖率和雾滴粒径。采用DPS 16.05统计软件对数据进行方差分析和显著性检验（Ducan’s新复极差法）。试验结果表示为平均值(mean)±标准差(SD)。

$$\text{叶面沉积量}/(\mu g\cdot cm^{-2})=\frac{\text{洗涤液的诱惑红质量浓度}(\mu g\cdot mL^{-1})\times\text{体积}(mL)}{\text{叶面积}(cm^{2})\times 2};\quad(1)$$

$$\text{利用率}/\%=\frac{\text{单株苹果的实际沉积量}(\mu g\cdot cm^{-2})}{\text{单株苹果的理论沉积量}(\mu g\cdot cm^{-2})}\times 100;\quad(2)$$

$$\text{地面沉积}/(\mu g\cdot cm^{-2})=\frac{\text{洗涤液的诱惑红质量浓度}(\mu g\cdot mL^{-1})\times\text{体积}(mL)}{\text{培养皿底面积}(cm^{2})};\quad(3)$$

$$地面流失率/\%=\frac{地面沉积量（\mu g\cdot cm^{-2}）\times 小区面积（m^2）\times 10}{小区内诱惑红投放量（mg）}\times 100。 \quad （4）$$

2　结果与分析

2.1　诱惑红标准吸收曲线的测定

对诱惑红水溶液进行吸光度检测，发现吸光度与诱惑红水溶液的质量浓度在0~65 μg·mL^{-1}范围内呈线性相关。一元线性回归方程为y = 0.050 2x−0.060 6，R^2=0.995 4。

2.2　不同牵引速度用水量的比较

牵引速度1.16 m·s^{-1}的单位用水量(284.63 L·666.7 m^{-2})约为速度1.77 m·s^{-1}(148.25 L·666.7 m^{-2})的1.5倍(表1)。

表1　不同牵引速度的用水量

Table 1　The water consumption of different traction speed

牵引速度 Traction speed/（m·s^{-1}）	总用水量 Total water consumption/L	喷施面积 Spraying area/m^2	用水量 Water consumption/（L·666.7 m^{-2}）
1.16	16.67	75	148.25
1.77	11.00	75	97.83

2.3　不同牵引速度的雾滴特性比较

由表2可知，在试验果园中，3WF-1000型风送式塔型喷雾机两个牵引速度(1.16 m·s^{-1}和1.77 m·s^{-1})在不同采样点的雾滴覆盖率分布范围为53.56%~67.37%，雾滴粒径为116.67~154.33 μm，雾滴密度为111.50~245.36点•cm^{-2}。喷雾机的雾滴覆盖率、雾滴粒径和雾滴密度因牵引速度不同而存在显著差异，其中，喷雾机牵引速度为1.16 m·s^{-1}时平均雾滴覆盖率和雾滴粒径分别为62.19%和142.67 μm，均显著高于牵引速度为1.77 m·s^{-1}时(57.03%和131.67 μm)；而雾滴密度则相反，牵引速度为1.16 m·s^{-1}时是141.72点•cm^{-2}，显著低于牵引速度1.77 m·s^{-1}时(179.86点•cm^{-2})(p<0.05)。

牵引速度不同，喷雾机在树体东、南、西、北和中方位的雾滴参数也不同。喷雾机牵引速度为1.77 m·s^{-1}时雾滴覆盖率在东、西、南和北4个方位均低于牵引速度为1.16 m·s^{-1}时，而在树体中部方位则相反，显著高于牵引速度为1.16 m·s^{-1}时(p<0.05)；雾滴粒径在5个方位均低于牵引速度为1.16 m·s^{-1}时，其中，南方位的雾滴粒径差异显著(p<0.05)；雾滴密度在树体东、西、北、中4个方位均高于牵引速度为1.16 m·s^{-1}时，而南方位雾滴密度略低于牵引速度1.16 m·s^{-1}。

表2　不同牵引速度的雾滴特性比较

Table 2　The droplet characteristics of different traction speed

指标 Index	方位 Orientation	牵引速度 Traction speed/（m·s^{-1}）	
		1.16	1.77
雾滴覆盖率 Droplet coverage/%	东 East	58.03±1.86 a	53.56±4.72 a
	西 Weast	67.37±6.31 a	57.02±2.26 a
	南 South	66.63±2.16 a	54.63±3.87 a
	北 North	64.73±2.34 a	60.03±2.80 a
	中 Middle	54.19±0.98 b	59.93±2.11 a
	平均 Average	62.19±6.05 a	57.03±3.92 b
雾滴粒径 Volume median diameter (VMD) of drop/μm	东 East	152.33±8.14 a	148.67±3.79 a
	西 Weast	154.33±3.06 a	148.00±17.35 a
	南 South	148.67±4.62 a	120.00±12.49 b
	北 North	139.33±4.04 a	125.00±11.27 a
	中 Middle	118.67±8.33 a	116.67±12.66 a
	平均 Average	142.67±14.45 a	131.67±17.73 b
雾滴密度 Droplet density/（Points·cm^{-2}）	东 East	124.07±15.85 a	127.93±11.92 a
	西 Weast	111.50±8.39 b	153.03±10.94 a
	南 South	146.99±6.24 a	135.34±15.47 a
	北 North	157.31±8.07 b	237.61±18.56 a
	中 Middle	168.74±3.93 b	245.36±15.89 a
	平均 Average	141.72±23.23 b	179.86±54.29 a

注：同一行中不同小写字母表示 5%水平上差异显著。下同。

Note: Different small letters in the same line indicate significant differences at the 5% level. The same below.

2.4　不同牵引速度的雾滴沉积分布和地面流失比较

3WF-1000型风送式塔型喷雾机喷施雾滴在叶面的沉积结果显示(表3)，喷雾机在两个牵引速度(1.16 m·s^{-1}和1.77 m·s^{-1})的叶面沉积量、地面沉积量、农药利用率和地面流失率的分布范围分别为0.16~0.30 μg·cm^{-2}、0.43~0.55 μg·cm^{-2}、43.7%~47.1%和19.4%~36.0%；喷雾机牵引速度为1.77 m·s^{-1}时叶面平均沉积量、地面沉积量、农药利用率和地面流失率分别为0.24 μg·cm^{-2}、0.55 μg·cm^{-2}、47.1%和36.0%，均高于牵引速度为1.16 m·s^{-1}时(分别为0.22 μg·cm^{-2}、0.43 μg·cm^{-2}、43.7%和19.4%)。

喷雾机的两个牵引速度(1.16 m·s^{-1}和1.77 m·s^{-1})在树体不同冠层内膛和外膛的雾滴沉积量均为上部冠层＞中部冠层≥下部冠层，且在树体中、下部冠层

表 3 不同牵引速度的雾滴沉积分布和地面流失

Table 3 The droplet deposition distribution and ground deposition of different traction speed

牵引速度 Traction speed/(m·s-1)	冠层 Canopy	叶面沉积量 Foliar deposition/(μg·cm-2)		沉积比 Ratio/(Inner/ Outer)	平均沉积量 The average of sediment weight/ (μg·cm-2)	利用率 Utilization ratio/%	地面沉积量 Ground deposition/ (μg·cm-2)	地面流失率 Ground loss index/%
		内膛 Internal	外膛 External					
1.16	上 Upper	0.24±0.03 a	—	—	0.22±0.04 a	43.7	0.43±0.06 b	19.4
	中 Middle	0.18±0.01 bc	0.25±0.02 a	0.72				
	下 Lower	0.16±0.02 c	0.25±0.01 a	0.64				
1.77	上 Upper	0.23±0.02 a	—	—	0.24±0.05 a	47.1	0.55±0.04 a	36.0
	中 Middle	0.22±0.01 ab	0.30±0.05 a	0.73				
	下 Lower	0.17±0.05 c	0.26±0.03 a	0.65				

的外膛药液沉积量均高于内膛。喷雾机在牵引速度为1.77 m·s-1时除了在树体上部冠层内膛药液沉积量略低外，在中、下冠层内膛和外膛的药液沉积量（内/外膛的沉积比为0.73和0.65）均高于牵引速度为1.16 m·s-1时（内/外膛的沉积比为0.72和0.64），但喷雾机两个牵引速度在树体上、中、下冠层内膛和外膛的药液沉积量差异不显著（$p<0.05$）。

3 讨 论

先进的施药器械辅以精准的施药技术，能有效降低农药的使用量，大幅度提高农药利用率。目前，中国现代矮砧宽行密植果园中，大中型风送式喷雾机已开始普及，但由于风送式喷雾机的研发和田间应用脱节，在应用中未能发挥风送式喷雾机的最佳性能，导致农药的使用效率低下，因此，综合评价施药器械在田间的施药效果并优化喷施过程中的各项技术参数显得尤为重要[22]。衡量药械施药效果的必备检测指标包含雾滴覆盖率、雾滴粒径、雾滴密度、药液利用率和流失率[18]，其中雾滴粒径和雾滴密度受施药机械的直接影响，最终影响药液的沉积量[22]。

摩泽[23]提出，对虫害的防治仅需5%的雾滴覆盖率，而对植物病害的防治则需要40%的雾滴覆盖率，通常覆盖率达到33%左右即可同时有效防治病害与虫害。生物最佳粒径理论证明，防治飞行害虫适合使用10~50 μm的细小雾滴，防治叶面爬行类害虫幼虫和植物病害则适合30~150 μm的雾滴[24-26]。丁素明等[27]报道，由于单个雾滴所产生的影响远大于其本身的粒径范围，雾滴密度达到20点•cm-2以上即可对病虫害有较好的防治效果。在本研究中，3WF-1000风送式塔型喷雾机两个牵引速度（1.16 m·s-1和1.77 m·s-1）的雾滴覆盖率为53.56%~67.37%，雾滴粒径为116.67~154.33 μm，雾滴密度为111.50~245.36点•cm-2，均能满足病虫害防治的基本要求。

在本研究中，与牵引速度为1.16 m·s-1时相比，3WF-1000风送式塔型喷雾机牵引速度为1.77 m·s-1时的雾滴覆盖率和雾滴粒径均由牵引速度为1.16 m·s-1时的62.19%和142.67 μm下降到57.03%和131.67 μm，而雾滴密度由141.72点•cm-2增加到179.86点•cm-2。这与袁会珠等[24]报道的在不同牵引速度下的喷雾机雾滴粒径和雾滴密度变化成反比相一致。喷雾机在树体东、南、西、北和中方位的雾滴参数因牵引速度的不同而不同，这可能与树体枝叶的疏密程度、喷雾机的行走方向及果树栽植行向有关。

农药利用率为农药喷施后沉积在靶标作物上的药量占总施药量的百分比[22]，是衡量药械喷施效率的重要指标。在本研究中，3WF-1000风送式塔型喷雾机的两个牵引速度（1.16 m·s-1和1.77 m·s-1）的农药利用率（43.7%和47.1%）均高于中国植保机械农药利用率的平均水平（36.6%）[2]；喷雾机牵引速度为1.16 m·s-1的地面流失率（19.4%）低于Vercruysse等[28]所研究的苹果园地面流失率（29%），而牵引速度为1.77 m·s-1时的地面流失率（36.0%）较高，推测可能是快速行驶时输送的风量和雾滴数量降低、雾滴叶面沉积量下降造成的[29]。喷雾机两个牵引速度（1.16 m·s-1和1.77 m·s-1）在树体中、下部冠层的内/外膛的沉积比均小于1，反映出树冠中下部内膛沉积量小于外膛，雾滴穿透效果较差。而苹果树作为多年生作物，轮纹病、腐烂病等枝干病害严重，内膛沉积量小不利于防治干部病虫害，可通过增加喷雾机压强或使用雾化效果更好的喷头以减小雾滴粒径，提高雾滴的穿透性。

4 结　论

3WF-1000型风送式塔型喷雾机两个牵引速度（1.16 $m \cdot s^{-1}$和1.77 $m \cdot s^{-1}$）的雾滴特性均能满足矮砧宽行密植苹果园病虫害的防治要求。喷雾机的两个牵引速度（1.16 $m \cdot s^{-1}$和1.77 $m \cdot s^{-1}$）在树体不同冠层内膛和外膛雾滴沉积量均为上部冠层＞中部冠层≥下部冠层，且在树体中、下部冠层的外膛药液沉积量均高于内膛，其中，喷雾机在牵引速度1.77 $m \cdot s^{-1}$时农药利用率更高，但易导致土壤流失率增高。

参考文献 References：

[1] 刘园园. 我国农村面源污染防治法律制度研究[D]. 杨凌：西北农林科技大学，2019.
LIU Yuanyuan. Study on the legal system of prevention and control of non-point source pollution in rural China[D]. Yangling: Northwest A & F University，2019.

[2] 苏小记，王雅丽，魏静，黄崇春，刘艾英，李淑，梁自静，袁会珠. 9种植保机械防治小麦穗蚜的农药沉积率与效果比较[J]. 西北农业学报，2018，27(1)：149-154.
SU Xiaoji，WANG Yali，WEI Jing，HUANG Chongchun，LIU Aiying，LI Shu，LIANG Zijing，YUAN Huizhu. Pesticide deposition percentage and control effect of nine kinds of crop protection machineries against wheat aphid[J]. Acta Agriculturae Boreali-occidentalis Sinica，2018，27(1)：149-154.

[3] 李丽，李恒，何雄奎，ANDREAS H. 红外靶标自动探测器的研制及试验[J]. 农业工程学报，2012，28(12)：159-163.
LI Li，LI Heng，HE Xiongkui，ANDREAS H. Development and experiment of automatic detection device for infrared target[J]. Transactions of the Chinese Society of Agricultural Engineering，2012，28(12)：159-163.

[4] 董涛. 基于表面增强拉曼光谱的土壤农残快速检测方法研究[D]. 杭州：浙江大学，2019.
DONG Tao. Study on rapid detection of soil pesticide residues based on surface enhanced raman spectroscopy[D]. Hangzhou: Zhejiang University，2019.

[5] 韩明玉. 苹果矮砧集约栽培技术模式刍议[J]. 中国果树，2015(3)：76-79.
HAN Mingyu. A preliminary discussion on the intensive cultivation technology model of apple dwarf rootstock[J]. China Fruits，2015(3)：76-79.

[6] 徐广春，顾中言，徐德进，许小龙，董玉轩. 常用农药在水稻叶片上的润湿能力分析[J]. 中国农业科学，2012，45(9)：1731-1740.
XU Guangchun，GU Zhongyan，XU Dejin，XU Xiaolong，DONG Yuxuan. Wettability analysis of pesticides on rice leaf[J]. Scientia Agricultura Sinica，2012，45(9)：1731-1740.

[7] 冯建国，张小军，于迟，陈维韬，蔡梦玲，吴学民. 我国农药剂型加工的应用研究概况[J]. 中国农业大学学报，2013，18(2)：220-226.
FENG Jianguo，ZHANG Xiaojun，YU Chi，CHEN Weitao，CAI Mengling，WU Xuemin. General situation of applied studies on pesticide formulations processing in China[J]. Journal of China Agricultural University，2013，18(2)：220-226.

[8] 徐德进，徐广春，许小龙，顾中言. 施液量、雾滴大小、叶片倾角及助剂对农药在稻叶上沉积的影响[J]. 西南农业学报，2015，28(5)：2056-2062.
XU Dejin，XU Guangchun，XU Xiaolong，GU Zhongyan. Effect of application volume，droplet size，rice leaf incline angle and spray adjuvant on pesticide deposition[J]. Southwest China Journal of Agricultural Sciences，2015，28(5)：2056-2062.

[9] NUYTTENS D，WINDEY S，BRAEKMAN P，DE MOOR A，SONCK B. Optimisation of a vertical spray boom for greenhouse spraying applications[J]. Communications in Agricultural and Applied Biological Sciences，2003，68(4 Pt B)：905-912.

[10] SÁNCHEZ- HERMOSILLA J，RINCÓN V J，PÁEZ F，FERNÁNDEZ M. Comparative spray deposits by manually pulled trolley sprayer and a spray gun in greenhouse tomato crops[J]. Crop Protection，2012，31(1)：119-124.

[11] 朱金文，吴慧明，朱国念. 雾滴大小与施药液量对草甘膦在空心莲子草叶片沉积的影响[J]. 农药学学报，2004，6(1)：63-66.
ZHU Jinwen，WU Huiming，ZHU Guonian. Influence of droplet size and spray volume on deposition of glyphosate on *Alligator* weed leaves[J]. Chinese Journal of Pesticide Science，2004，6(1)：63-66.

[12] 顾中言. 植物的亲水疏水特性与农药药液行为的分析[J]. 江苏农业学报，2009，25(2)：276-281.
GU Zhongyan. Analysis of the relationship between hydrophilic or hydrophobic property of plant and action of pesticides solution on plants leaves[J]. Jiangsu Journal of Agricultural Sciences，2009，25(2)：276-281.

[13] 袁会珠，齐淑华，杨代斌. 药液在作物叶片的流失点和最大稳定持留量研究[J]. 农药学学报，2000，2(4)：66-71.
YUAN Huizhu，QI Shuhua，YANG Daibin. Study on the point of Run-off and the maximum retention of spray liquid on crop leaves[J]. Chinese Journal of Pesticide Science，2000，2(4)：66-71.

[14] 洪晓燕，张天栋. 影响农药利用率的相关因素分析及改进措施[J]. 中国森林病虫，2010，29(5)：41-43.
HONG Xiaoyan，ZHANG Tiandong. Analysis of relevant factors influencing pesticide utilization and improvement measures[J]. Forest Pest and Disease，2010，29(5)：41-43.

[15] 何雄奎，严苛荣，储金宇，汪健，曾爱军，刘亚佳. 果园自动对靶静电喷雾机设计与试验研究[J]. 农业工程学报，2003，19(6)：78-80.
HE Xiongkui，YAN Kerong，CHU Jinyu，WANG Jian，ZENG Aijun，LIU Yajia. Design and testing of the automatic target detecting，electrostatic，air assisted，orchard sprayer[J]. Transactions of the Chinese Society of Agricultural Engineering，2003，

19(6):78-80.

[16] 胡桂琴. 果园风送喷雾机喷头雾化与沉积性能试验研究[D]. 南京:南京林业大学,2013.
HU Guiqin. Experimental study on automization and deposition characteristicof orchard air-assisted sprayer nozzle[D]. Nanjing: Nanjing Forestry University,2013.

[17] 李龙龙,何雄奎,宋坚利,王潇楠,贾晓铭,刘朝辉. 基于变量喷雾的果园自动仿形喷雾机的设计与试验[J]. 农业工程学报,2017,33(1):70-76.
LI Longlong,HE Xiongkui,SONG Jianli,WANG Xiaonan,JIA Xiaoming,LIU Chaohui. Design and experiment of automatic profiling orchard sprayer based on variable air volume and flow rate[J]. Transactions of the Chinese Society of Agricultural Engineering,2017,33(1):70-76.

[18] 张文君. 农药雾滴雾化与在玉米植株上的沉积特性研究[D]. 北京:中国农业大学,2014.
ZHANG Wenjun. The study of pesticide droplets atomization and deposit characteristics in corn leaves[D]. Beijing:China Agricultural University,2014.

[19] 亓文哲,王菲菲,孟臻,张典利,王红艳,乔康,姬晓雪. 我国植保无人机应用现状[J]. 农药,2018,57(4):247-254.
QI Wenzhe,WANG Feifei,MENG Zhen,ZHANG Dianli,WANG Hongyan,QIAO Kang,JI Xiaoxue. Application status of unmanned aerial vehicle for plant protection in China[J]. Agrochemicals,2018,57(4):247-254.

[20] 袁会珠,王忠群,孙瑞红,李世访,董崭,孙丽鹏. 喷洒部件及喷雾助剂对担架式喷雾机在桃园喷雾中的雾滴沉积分布的影响[J]. 植物保护,2010,36(1):106-109.
YUAN Huizhu,WANG Zhongqun,SUN Ruihong,LI Shifang,DONG Zhan,SUN Lipeng. Influences of nozzle type and spray adjuvant on the distribution of spray droplets with stretcher mounted sprayer in peach orchards[J]. Plant Protection,2010,36(1):106-109.

[21] 陈丹,任广伟,王秀芳,王新伟,冯超. 4种喷雾器在茶树上喷雾效果比较[J]. 植物保护,2011,37(5):110-114.
CHEN Dan,REN Guangwei,WANG Xiufang,WANG Xinwei,FENG Chao. Spray performance of four sprayers in the tea garden[J]. Plant Protection,2011,37(5):110-114.

[22] 程玲,薛光山,刘永杰,张安盛. 蔬菜病虫害防治中农药减量增效的影响因素及改进措施[J]. 农学学报,2018,8(2):11-14.
CHENG Ling,XUE Guangshan,LIU Yongjie,ZHANG Ansheng. Influencing factors and improving measures of pesticide decrement and synergism in vegetable pest control[J]. Journal of Agriculture,2018,8(2):11-14.

[23] 屠豫钦. 农药使用技术标准化[M]. 北京:中国标准出版社,2001:163-169.
TU Yuqin. Standardization of pesticide use technology[M]. Beijing:Standards Press of China,2001:163-169.

[24] 袁会珠,王国宾. 雾滴大小和覆盖密度与农药防治效果的关系[J]. 植物保护,2015,41(6):9-16.
YUAN Huizhu,WANG Guobin. Effects of droplet size and deposition density on field efficacy of pesticides[J]. Plant Protection,2015,41(6):9-16.

[25] 胡桂琴,许林云,周宏平,崔业民. 影响空心圆锥雾喷头雾滴粒径的多因素分析[J]. 南京林业大学学报(自然科学版),2014,38(2):133-136.
HU Guiqin,XU Linyun,ZHOU Hongping,CUI Yemin. Analysis of multi-factor influence on droplet size distribution of hollow cone nozzle[J]. Journal of Nanjing Forestry University (Natural Sciences Edition),2014,38(2):133-136.

[26] UK S. Tracing insecticide spray droplets by sizes on natural surfaces. The state of the art and its value[J]. Pesticide Science,1977,8(5):501-509.

[27] 丁素明,傅锡敏,薛新宇,周良富,吕晓兰. 低矮果园自走式风送喷雾机研制与试验[J]. 农业工程学报,2013,29(15):18-25.
DING Suming,FU Ximin,XUE Xinyu,ZHOU Liangfu,LÜ Xiaolan. Design and experiment of self-propelled air-assisted sprayer in orchard with dwarf culture[J]. Transactions of the Chinese Society of Agricultural Engineering,2013,29(15):18-25.

[28] VERCRUYSSE F,STEURBAUT W,DRIEGHE S,DEJONCKHEERE W. Off target ground deposits from spraying a semi-dwarf orchard[J]. Crop Protection,1999,18(9):565-570.

[29] 张海锋,许林云,徐业勇,蒋雪松,张慧春,贾志成,张昊天,徐铭铭. GY8果园喷雾机喷雾特性研究[J]. 南京林业大学学报(自然科学版),2015,39(1):135-141.
ZHANG Haifeng,XU Linyun,XU Yeyong,JIANG Xuesong,ZHANG Huichun,JIA Zhicheng,ZHANG Haotian,XU Mingming. Research on spray characteristics of GY8 orchard sprayer[J]. Journal of Nanjing Forestry University (Natural Sciences Edition),2015,39(1):135-141.