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RESEARCH ARTICLE

Operational Image Processing Approach for Spray Coverage Measurements in Pesticide Application

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ABSTRACT

Water sensitive papers (WSPs) are mostly used to determine the performance of spray systems used in pesticide application. The most critical stage of an image processing operation is determining the threshold level of WSP images. In this study, an analysis of WSP images was conducted using two thresholding methods. The first was a variable - defined approach (dependent), which determined the thresholding level according to the greyscale level of each WSP sample. The second approach was automated, where the thresholding level was automatically set by image processing software. Using both thresholding methods, the percent spray coverage of the WSP samples was determined using a macro module prepared using the software interface, and the results of both methods were compared. Overall, the spray coverage was high and measurement error was clearly observable for some of the WSP images using the automatic thresholding approach. The percent spray coverage of 17 out of 432 analysed WSP images was found to be 24 to 414 times higher when using the automatic as opposed to the dependent thresholding approach. In addition, extreme values for the percent spray coverage was observed for the automatic method. Our results suggest that percent spray coverage without extreme data can be quickly and practically determined for WSP images using a dependent, variable - defined thresholding method using a macro module.

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Introduction

In spray treatments, percent spray coverage can be determined by droplet sampling in the unit area, and water sensitive papers (WSPs) are often used as sampling materials for this purpose (Cunha et al., 2013; Nascimento et al., 2013; Cerruto et al., 2016; Lipiński and Lipiński, 2020). When droplets are formed as a result of spray coming into contact with WSP surfaces, a yellow film layer is formed and the contact area turns blue and forms spots. WSPs are also used to observe the effectiveness of the transport of droplets to a target (Nuyttens et al., 2004; Khot et al., 2011). The percent spray coverage of droplets on the surface of a paper can be calculated by analysing various image processing methods, as the total area of blue - coated stains on a paper's surface is proportional to the sampling area (Sayıncı and Bastaban, 2011b; Zhu et al., 2011; Cunha et al., 2012; Sayıncı et al., 2019a; Sayıncı et al., 2019b).

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WSPs can be used to check droplet density (number of droplets per cm^2) (Sayıncı et al., 2019c) for sprayer calibration. The spray application volume that should be applied to a unit area is adjusted according to the recommended minimum droplet density values used in pesticide applications (Matthews, 2000). In spray applications, droplet - size analysis is commonly performed using laser measurement systems. However, WSPs are inexpensive and practical for droplet diameter analysis, as droplet characteristics can be determined by sampling their surfaces. WSPs can be used to estimate the spherical diameter of a droplet based on the diameter of the spot measured from a specific sampling area (Sayıncı and Bastaban, 2011a; Salyani et al., 2013). Degré et al. (2001) used glass surfaces, silicone oil and WSP samples to compare sampling methods for droplet - size analysis. The authors reported that the silicon - oil method required precision and that small - diameter droplets on glass surfaces could not be analysed due to evaporation. Moreover, the authors found that droplet size was more easily analysed on WSP surfaces compared to the other sampling methods. However, they suggested that WSP samples should be protected from external environmental conditions for qualitative assessments.

Image processing methods are typically used to determine the percent spray coverage of WSP images, and a critical stage of this processing is the determination of the threshold level for the sample (Sayıncı and Bastaban, 2011a). This level, for an 8 - bit WSP image, ranges between 0 - 255 bits and is typically based on the subjective assessment of the operator (Sayıncı and Bastaban, 2009). Therefore, this study investigated practical approaches to minimize measurement errors when determining the percent spray coverage on WSP images and quickly perform the analysis of numerous WSP samples using a macro module.

Materials and Methods

Spray Simulator

A linear, moving - spray simulator was used for the spray applications (Figure 1). The rail length of the simulator (Figure 1a) was 12 meters and had a compact, linear - moving mechanism (Figure 1b) driven by a 1000 W, 0 - 5000 rpm, Delta ASDA - B2 servo motor (AutomatedPT, LLC, Dallas, TX, USA). The forward speed of the mechanism was automatically adjusted using the servo motor drive.

Figure 1. Spray simulator (a) rail of 12 meters (b) linear moving mechanism

Figure 2. Spray boom and hydraulic nozzles

There was a single - side spray boom on the moving mechanism and five nozzles were mounted at 50 cm intervals (Figure 2). The height of the spray boom was adjusted by changing the position of the frame on the mechanism. The forward speed of the spray simulator was calculated using the equation: $[V = (q \cdot 600)/(B \cdot N)]$ where *V* is the forward speed in km h^{-1}, *q* is the nozzle discharge, L min^{-1}, *B* the nozzle spacing at 0.50 m and *N* is the spray application rate at L ha^{-1}. A spray application rate of 80 L ha^{-1} was made from a height of 40 cm with four different types of flat - fan nozzles (Lechler ST110 - 015, ST80 - 015, SC120 - 025 and LU120 - 015) at a spray pressure of 200 kPa. The forward speed of the spray simulator at was adjusted according to the nozzles for constant application rate.

Hydraulic Pressure Unit

The flow line of the spray simulator was constructed from a sprayer with a 600 - litre tank capacity (TP600 Piton Taral®, Istanbul, Turkey) (Figure 3). A piston - membrane pump was used for the sprayer (a double - piston at a nominal pressure of 3.9 MPa, a nominal flow rate of 30 L min^{-1}, and 67% efficiency (Taral®)). The pump shaft was driven with an MSD 90L2 gear motor (Gamak, Istanbul, Turkey), and the sprayer tank was filled with tap water.

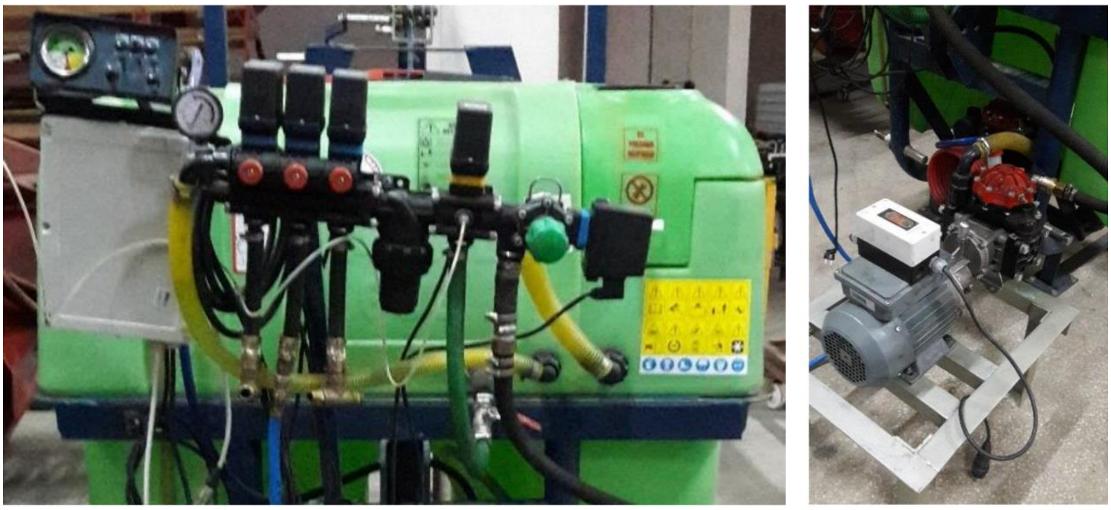

Figure 1. Sprayer and pressure - control unit

Sampling Method

WSPs (Syngenta AG, Basel, Switzerland) of 26 × 76 mm were used as spray - sample collectors in spray treatments. The WSP sampling method shown in Figure 4 was used to obtain samples with different percent coverages at a constant spray application rate (Sayıncı et al., 2019b).

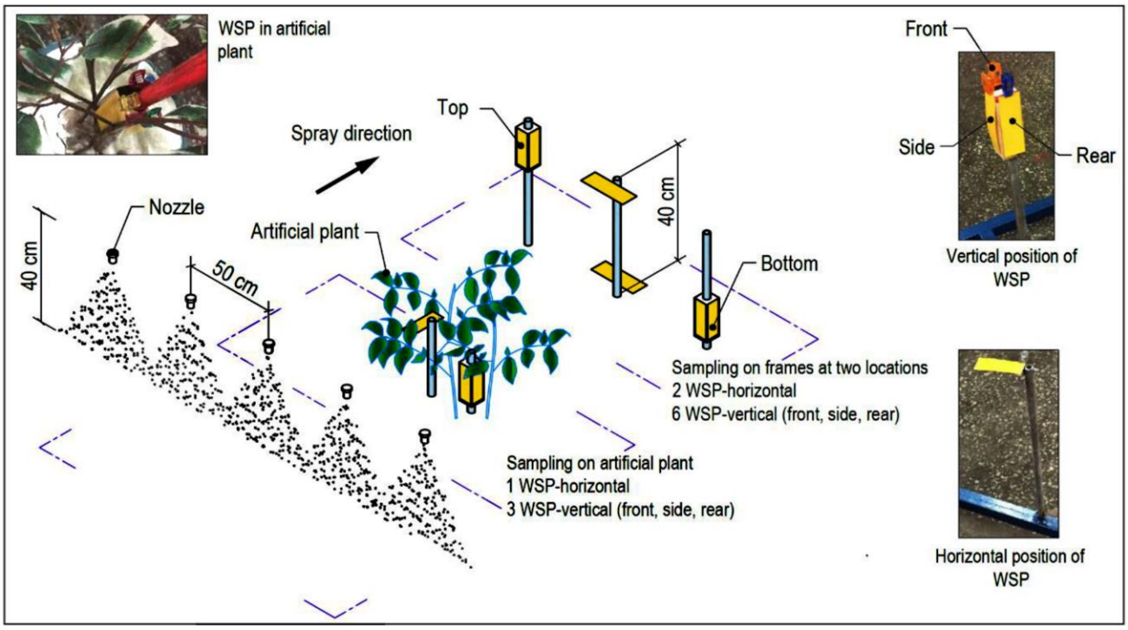

Figure 4. WSP sampling methodology

The tubular frames and artificial plants with the heights of 40 cm were used to position WSPs at different levels and positions. The WSPs were located both top and bottom parts of the frame and the artificial plant targets. In addition, the samples were positioned horizontally and vertically each of the targets. For the vertical orientation, the WSP samples were placed in an upright position on the front, side and rear surfaces of a square (30 × 30 × 80 mm) cross - section of wood. For the horizontal orientation, 10 × 100 mm sheet - metal plates were used and the WSPs were fixed parallel to the floor with a clip. The spray treatments were repeated 9 times. Accordingly, the WSP sampling were done at 3 levels (top, bottom and inside of the artificial plant canopy), 4 positions (horizontal, front, side, and rear) using 4 different types of the spray nozzles. All trials were conducted under controlled laboratory conditions with indoor temperature and relative humidity measured at 21 °C and 38%, respectively.

Image Processing Methods

Following spray treatment, the WSPs were collected and scanned at 600 dpi resolution using an HP Scanjet 4850 (Hewlett - Packard, Palo Alto, CA, USA) and converted to an 8 - bit (range 0 - 255) greyscale image. The images had a total of 256 (2^8) shades of grey, including black and white colours. As the threshold level approached 255, the spots on the image were covered in shades closer to black and, as they approach 0, they were covered in shades closer to white. The spot images were analysed using ImageJ 1.38x software (Wayne Rasband, National Institutes of Health, Bethesda, MD, USA). To determine spray coverage of the WSP images, automatic and dependent thresholding approaches were used.

For the automated approach, spray coverage was determined using automatic thresholding (t_a) that is option of the software interface. This process used the auto option on the threshold interface. However, to automatically analyse all of the WSP images in a short time a macro module was written (Figure 5).

```
% Open image file in WSP folder
open("F:\\WSP\\01.tif");
%Run automatic threshold option
setAutoThreshold();
%Accept the automatic threshold value
//run("Threshold...");
%Select "Area Fraction" option on "Set Measurements"
interface and set the decimal value to 5.
run("Set Measurements...", "  area_fraction redirect=None
decimal=5");
%Run Measure command for percent spray coverage. Report
data on result window
run("Measure");
%Close image file
close()
```

Figure 5. Macro module used to determine the percent spray coverage by the automatic thresholding method

For dependent thresholding, the percent spray coverage was based on the mean grey level (g) of each image. To determine this level, the macro module shown in Figure 6 was used, and the threshold level (t_g) of each image was calculated using Equation 1 (Sanchez - Hermosilla and Medina, 2004).

$$t_g = 0.38g + 78.75 \qquad (R^2 = 0.91) \qquad (1)$$

```
open("F:\\WSP\\01.tif")
%Select "Mean Grey Value" option on "Set Measurements"
interface
run("Set Measurements...", "  mean redirect=None
decimal=5")
run("Measure")
close()
```

Figure 6. Macro module used to determine the mean grey level of WSP images

The macro module shown in Figure 7 was given for only one WSP sample. For a functional image processing, the threshold level for each WSP image was defined separately in the macro module. After thresholding, the area fraction of the spots coating the WSP surfaces was measured using ImageJ software, and the results were recorded as the percent spray coverage. The area fraction was an option in the 'Set measurements' interface of the software. The macro modules ensured that all of WSP images were quickly analysed.

```
open("F:\\WSP\\01.tif")
setAutoThreshold();
//run("Threshold...");
%Set dependent threshold level of WSP image (Lower
threshold level= 0; Upper threshold level= 147).
setThreshold(0, 147);
run("Set Measurements...", "  area fraction redirect=None
decimal=5");
run("Measure");
close();
```

Figure 7. Manual threshold level definition for each WSP image and calculation of the percent spray coverage

Statistical Analyses

The factors effecting the mean greyscale levels of the WSP images were tested with analysis of variance (ANOVA), and the partial eta squared statistic was taken into account in order to determine the factor that best describing the variance. A paired sample t - test was used to test the significance of the difference between two thresholding approaches. SPSS version 20.0 statistical software was used for the statistical tests.

Results

The first stage of this study was to obtain WSP images with different greyscale levels. The results of the variance analysis in Table 1 showed that the main variance sources were statistically very significant. The greyscale levels of the WSP images varied between 132.7 - 182.7. The images collected from the horizontal position had the lowest mean greyscale level. In general, the mean greyscale level of the images taken from the artificial plant higher than those of the other locations. In reference to the partial eta squared statistics, the position variable clarified the variance at the rate of 81.2% among the variation sources.

Table 1. Comparison of greyscale levels of WSP images according to the sampling methodology

A. Result of the variance analysis (: very significant P < 0.01; ns: no - significant)**

Variation sources	df	Mean square	F	Sigma (P)	Partial Eta Squared
Nozzle (N)	3	190.602	11.622	0.0000**	0.080
Location (L)	2	2652.383	161.729	0.0000**	0.446
Position (P)	3	9472.169	577.566	0.0000**	0.812
N × P	9	324.106	19.762	0.0000**	0.307
N × L	6	19.395	1.183	0.3150^{ns}	0.017
L × P	6	712.692	43.456	0.0000**	0.393
Error	402	16.400			
Total	431				

B. Mean greyscale levels of WSP images

Positions	Nozzle types	Sampling locations (mean ± SD)		
		Top	Bottom	Plant
Horizontal	LU120 - 015	139.9 ± 6.9	149.0 ± 3.4	163.1 ± 2.1
	SC120 - 025	142.4 ± 2.3	146.9 ± 3.6	163.1 ± 2.6
	ST110 - 015	154.4 ± 2.1	160.4 ± 1.4	171.4 ± 1.5
	ST80 - 015	140.4 ± 3.1	147.7 ± 1.5	161.7 ± 5.5
	Mean ± SD	144.3 ± 7.2	151.0 ± 6.1	164.8 ± 5.0
Front	LU120 - 015	170.9 ± 6.6	165.5 ± 6.5	174.8 ± 5.0
	SC120 - 025	169.6 ± 5.2	168.1 ± 6.1	173.7 ± 4.0
	ST110 - 015	165.0 ± 4.9	167.2 ± 3.7	172.9 ± 4.4
	ST80 - 015	165.2 ± 2.2	163.3 ± 6.7	171.7 ± 3.8
	Mean ± SD	167.6 ± 5.5	166.0 ± 5.9	173.3 ± 4.3
Side	LU120 - 015	173.1 ± 4.7	175.1 ± 3.6	176.9 ± 4.7
	SC120 - 025	172.2 ± 2.1	174.6 ± 4.0	175.8 ± 4.2
	ST110 - 015	169.5 ± 2.1	171.7 ± 3.4	173.5 ± 4.1
	ST80 - 015	169.2 ± 0.9	174.5 ± 4.3	172.5 ± 3.2
	Mean ± SD	171.0 ± 3.2	174.0 ± 3.9	174.7 ± 4.3
Rear	LU120 - 015	174.2 ± 2.7	174.4 ± 4.1	176.8 ± 4.4
	SC120 - 025	171.5 ± 3.3	174.3 ± 4.5	174.0 ± 3.6
	ST110 - 015	166.7 ± 3.4	172.3 ± 4.0	173.9 ± 4.4
	ST80 - 015	169.0 ± 1.8	175.1 ± 3.9	172.5 ± 3.9
	Mean ± SD	170.3 ± 3.9	174.0 ± 4.1	174.3 ± 4.2
All data (min - max)		142.7 - 182.5	157.3 - 182.7	132.7 - 180.4

The mean greyscale levels for a selection of WSP samples with different percent spray coverages were shown in Figure 8, which demonstrates that these levels increased as the percent spray coverage decreased visually. Sample 1 and Sample 5 images had the lowest and the highest greyscale levels, respectively, among the WSP samples.

The results of the paired simple t - test related to spray coverage ratios (%) determined with the automatic and dependent thresholding methods were given in Table 2. The difference between both thresholding methods for the WSP images taken from the front and side surfaces of the upright position was statistically insignificant (P > 0.05). Notwithstanding, spray coverage ratios of the WSP samples collected from the horizontal surface and rear surface of the vertical position were found different in reference to the paired simple t - test (P < 0.01).

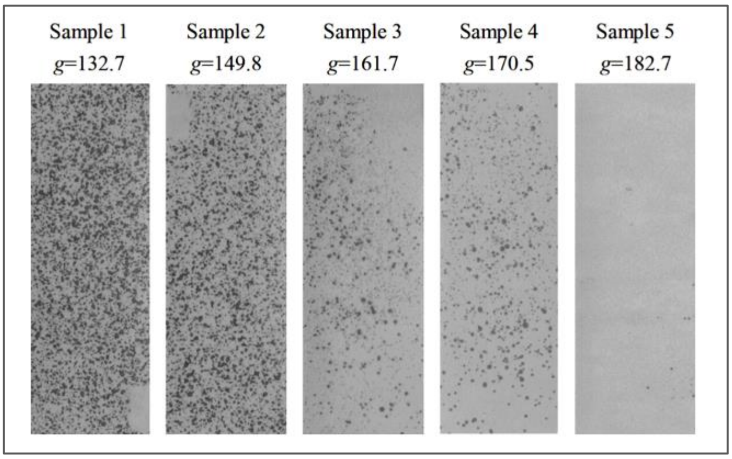

Figure 8. Mean greyscale levels (g) of some WSP images

Table 2. Paired simple t - test results

WSP position	Thresholding approaches (Spray coverage rate, %)		t	df	Sig. (2 - tailed)
	Automatic	Dependent			
Rear	3.90 ± 8.33	0.90 ± 1.13	3.65	107	0.0000**
Horizontal	14.48 ± 7.12	16.00 ± 7.68	- 9.17	107	0.0000**
Front	3.14 ± 3.52	3.31 ± 3.46	- 0.926	107	0.3560^{ns}
Side	1.23 ± 3.42	1.07 ± 1.23	0.475	107	0.6360^{ns}

**: very significant P < 0.01; ^{ns}: no - significant

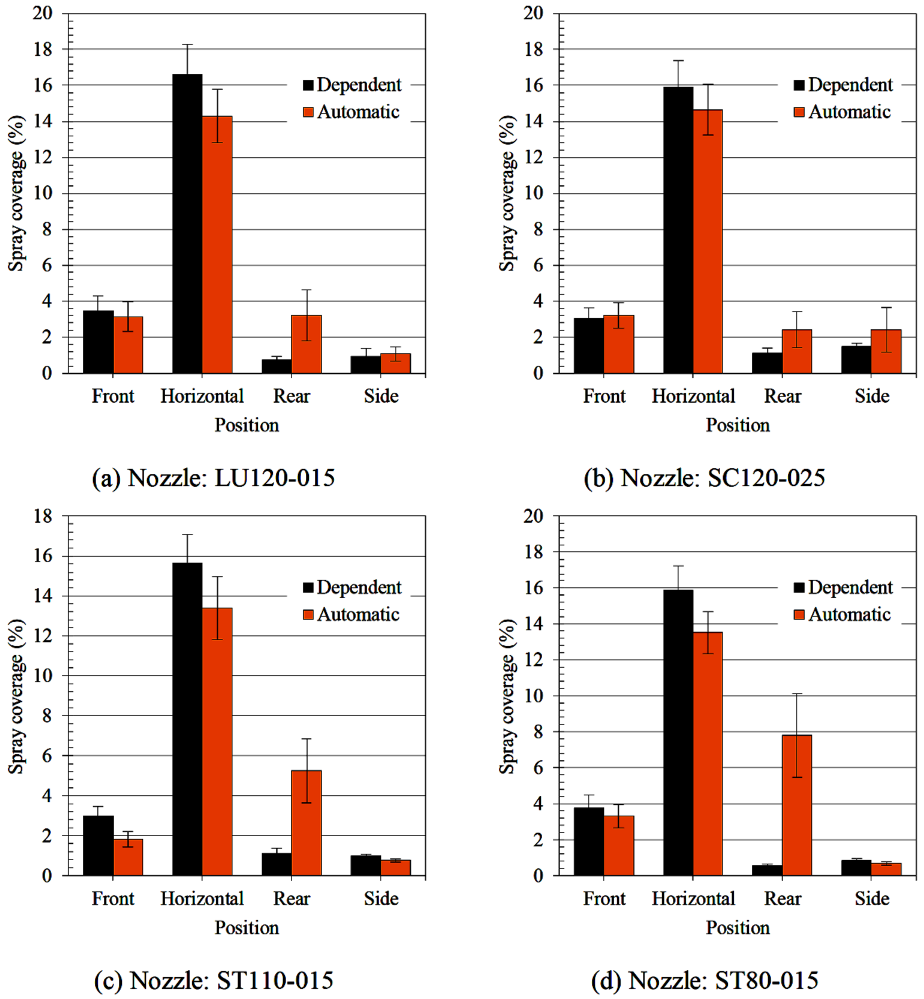

Figure 9. The variation of spray coverage means obtained from both thresholding methods according to the nozzle types (mean ± SE)

The variation of the spray coverage ratio obtained by both thresholding methods according to the nozzle types was shown in Figure 9. In most cases, the spray coverage ratio measured using the dependent thresholding approach was higher than those of the automatic thresholding. The reason for this is that the threshold levels determined based on the grey level of WSP are higher than those of the automatic thresholding method. However, the means of the automatic thresholding method increased prominently for the samples taken from the rear surfaces. The rear surface was the location where the most incorrect measurements were made in terms of the spray coverage. The substantially lower spray coverage for the WSP sample at the rear surface was measured as a higher value at the automatic thresholding method. The higher values were the outliers, and increased the standard error of the mean.

The relation between both thresholding approaches was shown on the logarithmic scale charts in Figure 10.

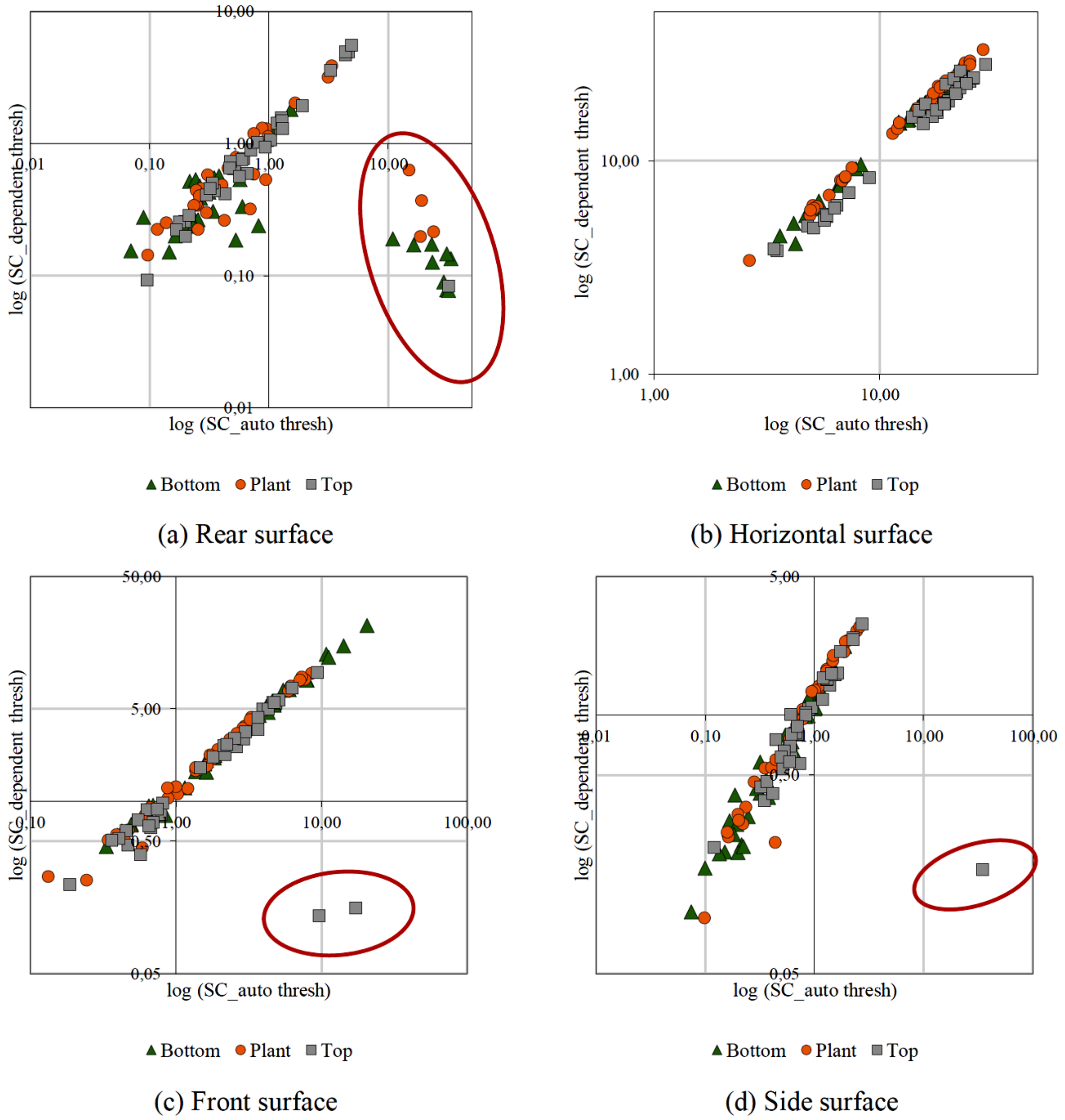

Figure 10. Comparison of spray coverage ratios measured by automatic and dependent thresholding methods

The incompatible spray coverage means in both measurement methods were seen as extreme values shown in circle. Most of the extreme values were in the samples taken from the rear surface, while there were a few extreme values on the front and side surfaces. No extreme value was found in the analysis made using both thresholding approaches on the horizontal surface. For the automatic thresholding method, 17 out of 432 WSP images had extreme values and their spray coverage ratio was 24 - 414 times higher when compared to the dependent thresholding method.

The images in Figure 11 show the differences between the automatic and dependent - variable thresholding methods.

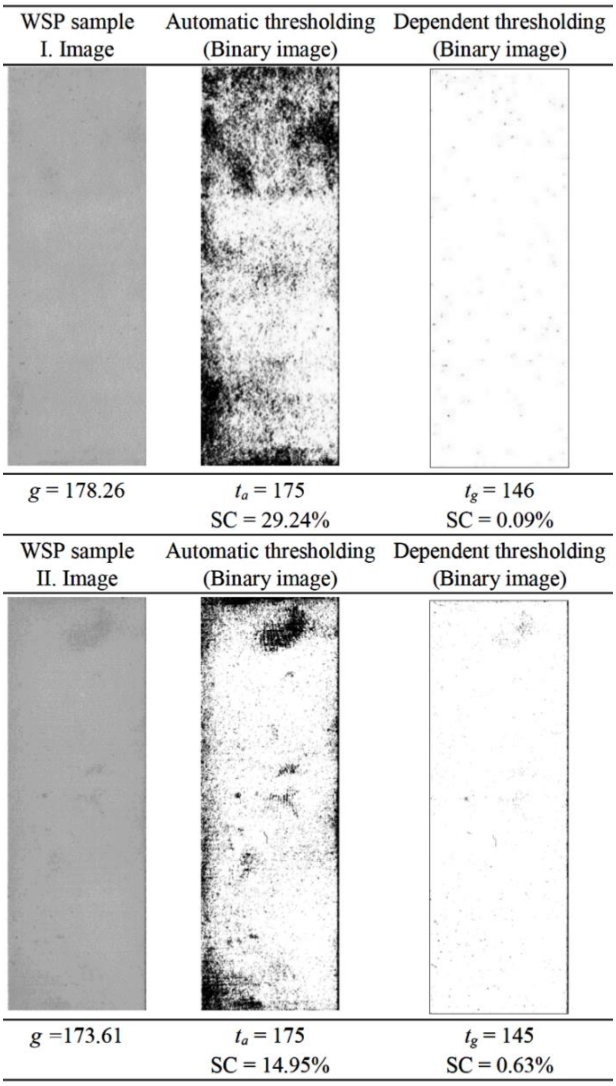

Figure 11. Effect of automatic and dependent thresholding methods on percent spray coverage (SC: spray coverage, %; g: mean greyscale level; ta: automatic thresholding; tg: dependent thresholding)

The mean greyscale levels of the first (I) and the second (II) WSP images are similar to one another, and the number of spots per unit area on both WSP surface images were quite low. However, the shaded areas on the WSP images in the automatic thresholding method can be easily observed and exhibited a considerable increase in the percent spray coverage.

Discussion

WSP samples used in spray treatments provide important information regarding spray quality. In research conducted on droplet spectrums, spray penetration, spray - distribution uniformity and droplet transfer to targets, WSPs are positioned on target surfaces (Fox et al., 2003; Cerruto et al., 2013; Salyani et al., 2013; Witton et al., 2018; Cunha et al., 2019) and collected after spray applications for individual analyses with different image - processing software (Cunha et al., 2012). The sampling methodology in the present study structured based on available the literature was constituted sensitively with the aim of obtaining the WSP samples with different spray coating rates. This precision was proved with the result of the variance analysis and the images with different greyscale level were obtained in the present study.

In the study conducted by Sayıncı et al. (2019b), the lowest spray coverage ratio was found at the rear target surfaces of the upright position, and this was considered an important problem for any spray application. Among the spray surfaces at horizontal and vertical positions, the highest drop transport was provided on the surfaces at horizontal position. WSP samples on the rear surface of the vertical position are behind the spray direction. Since WSP samples are mostly analysed individually, it is possible to detect WSP images where no drops are transferred. However, when a macro module is used to analyse hundreds of WSP samples of a spray application quickly and practically, it is not possible to detect WSP samples where no drops are transferred.

According to the paired sample t - test results, one of the most important findings of this study is that the spray coverage ratio determined by the dependent thresholding method is higher than the automatic thresholding method based on horizontal surface data. This finding does not mean that the spray coverage is measured incorrectly. This difference between the two thresholding methods is based on the boundary conditions accepted at the beginning of the image processing. The second most important finding is that in the lowest WSP samples, the spray coverage ratio determined by the automatic thresholding method is higher than the dependent thresholding. This second finding shows that the spray coverage was measured incorrectly in the automatic thresholding method.

In this study, as a number of droplets per unit area of the sampling surface increased, the mean grey level of the WSP images decreased, and the mean grey level of the images under conditions where no droplets had transferred had the highest values. In addition, there were significant differences in the spray coverage data determined by the automatic and dependent thresholding methods. These differences were particularly noticeable in the WSP images with the lowest droplet densities. In the automatic thresholding method, unstained areas on most of the WSP images included the stained selection due to the colour fluctuations on the yellow surface after thresholding. Hence, the shaded areas on WSP images after automatic thresholding were covered as though they were droplets, included into spray coverage ratio and caused unexpected increases in the values.

Conclusion

Though automatic thresholding is considered ideal for practical analyses, it was concluded that the percent spray coverage contains extreme values. In contrast, the threshold level of each WSP image using dependent thresholding needed to be determined according to the mean grey level of the image, which reduced reliance on the operator’s judgment. Therefore, dependent thresholding can reduce measurement error and enable analyses to be carried out practically and quickly when using a macro module.

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