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Research Paper

Experimental method for the assessment of agricultural spray retention based on high-speed imaging of drop impact on a synthetic superhydrophobic surface

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Spray retention is a critical stage in pesticide application since non-retained drops can result in reduced efficacy, economic loss and environmental contamination. Current methods of retention assessment are based either on field experiments or laboratory studies. The former are usually performed on whole plants under realistic spray application conditions but offer no insight into the physics behind the process whilst the latter mainly focus on drop impact physics but are usually restricted to unrealistically low drop speeds. The aim of the paper is to devise an experimental method to investigate retention at drop scale level as a function of operational parameters but under controlled realistic conditions. A device based on high-speed video was developed to study retention on a synthetic superhydrophobic surface for a moving agricultural nozzle. The sizes and velocities of the drops generated were measured immediately before impact using image analysis. Impact class proportions were established and transition boundaries between impact outcomes were quantified using Weber number. Two contrasting experiments were performed to investigate the ability of method to detect small parametric changes. The insignificant changes in spray pattern that occur from pressure changes, did not significantly affect impact class boundaries, but changed the proportion of drops in each class because of size and velocity variations. The use of a surfactant reduced the volume median diameter of the spray, increased impact speed and changed the impact class boundaries. The method should allow a precise parametric investigation of spray retention in laboratory and close to field conditions.

1. Introduction

Pesticide application efficiency improvement is required for health, safety, environmental and cost considerations. Zabkiewicz (2007) divided the measurement of the spray application process in 4 individual stages, namely *deposition*, defined as the amount deposited in the target area; *retention*, the fraction of drops captured by plant; *uptake*, the fraction of the retained material taken up into plant foliage and *translocation*, the amount of absorbed material translocated from absorption site. Depending on the scenario, it was estimated that the efficiency of the deposition process was in the 80–95 % range whilst the retention process was in the 10–100% range, resulting in a combined worst case efficiency of 8%. Much research has therefore been devoted to minimise these losses, either by improvements in spray technology or the

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Nomenclature

μ	liquid dynamic viscosity, Pa s
d	drop diameter, m
DST	dynamic surface tension, N m^{-1}
LAI	leaf area index, m^2 leaf per m^2 ground
Oh	Ohnesorge number, dimensionless
Re	Reynolds number, dimensionless
v	drop velocity before impact, m s^{-1}
VMD	volumetric median diameter, μm
We	Weber number, dimensionless
$\mathrm{We}_{A/F}$	Weber number for adhesion/fragmentation boundary, dimensionless
$\mathrm{We}_{A/R}$	Weber number for adhesion/rebound boundary, dimensionless
$\mathrm{We}_{R/F}$	Weber number for rebound/fragmentation boundary, dimensionless
σ	liquid static surface tension, N m^{-1}

physicochemical properties of the pesticide formulation, the objective being to decrease the amount of chemical applied per unit area whilst ensuring that the dose of chemical required for control reaches the target.

Some spray application studies have focussed on deposition and retention as a whole at plant scale. Butler Ellis, Webb, and Western (2004) examined the effect of liquid properties and application technology on spray retention in a range of situations representative of practical pesticide application. Retention on whole plants was strongly influenced both by plant growth and plant canopy. Changes in pesticide application method from conventional flat-fan to air induction nozzle had a detrimental effect. Leaf surface was influenced by age and growing conditions with indoor grown plants being more difficult-to-wet than outdoor grown plants due to leaf surface abrasion. Lower dynamic surface tension (DST) improved retention, especially when using an air induction nozzle on difficult-to-wet leaves. These results show that retention process is governed by numerous factors: drop size and velocity, physicochemical properties of spray formulation, spatial distribution within the canopy and target surface properties. This approach provided an integrated estimate of the deposition and retention but failed to develop a fundamental understanding of the physics behind the processes.

Some research has focussed on the retention phase at the drop scale. Drop impact was then studied using imaging devices and drop generators (Yang, Madden, Reichard, Fox, & Ellis, 1991). This approach was used by Forster, Kimberley, and Zabkiewicz (2005) to devise a statistical model based on extensive experimental work to predict the adhesion/bounce transition. The parameters or combination of parameters used were the product of velocity and drop diameter, leaf angle, leaf surface and formulation surface tension. Shattering is not usually observed in these studies. Monodisperse drops were produced, using either on demand or continuous drop generators (Reichard, Cooper, Bukovac, & Fox, 1998). On demand droplet generators are usually restricted to generating drops at their terminal velocities at best and a single drop is produced at a time. Continuous drop generators have the advantage to produce higher speed drops but they are however limited in size by the orifice diameter and aerodynamic interactions with the surrounding air (Sirignano & Mehring, 2000).

While an overall approach to measurement can highlight the effects of nozzle drop size spectra, measurements at drop scale fail to produce drop size and velocity distributions representative of agricultural nozzles. However, both approaches highlight the major influence of leaf wettability on the retention process. Wettability refers to the drop behaviour on the leaf surface. The diversity of plant and their surface structures led a wide range of wetting, from superhydrophilic to superhydrophobic (Koch & Barthlott, 2009). Gaskin, Steele, and Forster (2005) proposed a method to rank plant surfaces using acetone–water contact angle measurements. Easy-to-wet leaves retain most of the drops while difficult-to-wet ones, such as blackgrass or wheat, are difficult to treat. More particularly, the hydrophobic behaviour of leaves usually originates from their waxy cuticles. If the leaf coating is composed of hydrophobic crystal waxes that generate small-scale roughness, this may result in superhydrophobicity (Taylor, 2011). Unfortunately, because of the variability of superhydrophobic natural leaf surfaces, retention studies face reproducibility limitations. When comparisons of small operational variations such as changes in pressure or adjuvants are conducted, serious limitations on sensitivity may result.

Manufacturers are interested in clarifying the relationship between pesticide application methods and the physicochemical properties of the pesticide formulation and spray retention to guide their technical developments. To support this objective, a theoretical review that links drop dynamics and impact outcome for superhydrophobic surfaces is presented. Using this theoretical basis, an assessment method is proposed to analyse the physics of drop retention at the drop scale under controlled and realistic conditions. A synthetic superhydrophobic surface is used to perform tests on a well-controlled target representative of difficult-to-wet leaves. Experiments performed at different operating pressures and surfactant concentrations were used to assess the performance of the method.

2. Theoretical background

Drop impact on superhydrophobic surfaces is considered in this section as the foundation for further work. The aim is to understand the connections between drop properties, wettability and impact behaviours on a superhydrophobic surface.

A drop hitting a surface exhibits different behaviours depending on drop size and velocity, liquid and surface properties. However, each impact begins with the same steps. The drop then spreads until it reaches its maximum spreading distance. Different options are possible depending on the surface wetting regime and the drop energy during impact.

Two models describe the wetting of superhydrophobic surfaces depending on the liquid surface tension (Taylor, 2011; Zu, Yan, Li, & Han, 2010). The Wenzel non-composite regime (Wenzel, 1936), often referred as pinning, is characterised by