Agri. & Biosys. Eng. Vol. 3(1):44-54(2002)

Recent Developments in Agricultural Sprays : Review

S. Y. No

Abstract: A brief review of current status in the field of agricultural spray and future research challenges are presented. Researches on the pesticides sprays, pollen sprays, postharvest sprays, and biological control agent sprays among the various applications of agricultural spray were selected and reviewed. In the agrochemical sprays, the techniques to increase the deposition such as electrospray and reduce the drift such as introductions of drift retardants and of mechanical means are reviewed. The introduction of mechanical means includes low drift, air-assisted, air inclusion, shield or shroud assisted and pulse flow nozzles.

For flat fan nozzles, the data of breakup length and thickness of liquid sheet are essential to understand the atomization processes and develop the transport model to target. In the air-assisted spray technology to reduce drift, further works on the effect of application height on drift and air assistance on droplet size should be followed. In addition, methods for quantifying the included air in the air inclusion techniques are required. The atomization characteristics of biopesticides spray are not being elucidated and the formulations of biopesticides should be taken into account the spray characteristics of existing nozzle and sprayer. A few researches on the droplet size of fallout can be found in the literature. A combined technology with electrostatic method into one of method for the reduction of drift may be an effective strategy for increasing deposition and reducing drift. Only an integrated approach involving all stakeholders such as engineers, chemists, and biologists, etc. can result in improved application of agricultural spray.

Keywords: Biopesticide spray, Electrospray, Pesticides spray, Pollen spray, Postharvest spray

Introduction

The spray and atomization technology in the field of agriculture is applied in the agrochemical or pesticides sprays, pollen sprays, postharvest sprays, biological control agent (biopesticides) sprays, fertilizer sprays, and growth regulator sprays etc. The fertilizer and growth regulator sprays are not discussed in this paper.

Pesticide applications to control agricultural diseases and pest are an important part of today's farming because the supply of the inexpensive and high quality product of many agricultural crops is required. However, the application of pesticides such as herbicide, insecticide and fungicide accompany contamination of surface and ground water, poisoning wild life, damage to non-target organisms, residue in foodstuffs and development of pesticide resistance.

The pesticide application in 1980 days was known as one of the most inefficient industrial process. The typical agricultural spray application generally results in spray deposition on less than 5% of the target with approximately 1% of the applied pesticide eventually being biologically active against the target pest(Hilsop, 1987). Although current agrochemical application methods and equipment have improved application accuracy considerably than those of 1980's, chemical spray application remains an inefficient operation. The goal of agricultural spray application should be, at first, biological effectiveness, the most effective form to the pest, secondly economy, at the lowest cost, thirdly, environmental friendlyness, no off-target effects. Thus the challenge for the agricultural engineer is to produce the pesticide application sprayers that can control the volume distribution of spray droplets on a wide range of different target crops, and enable advantage to be taken of different pest control strategies without raising any new environmental contamination problems.

Pollination of plants is an essential and important process of agriculture with many crops relying on adequate pollinator such as wind and animals for their

---

The author is **Soo Young No**, Professor, Department of Agricultural Machinery Engineering, Chungbuk National University, Cheongju, 361-763 Korea. Tel : +82(43) 261-2583. Fax : +82(43) 271-4413 Email : sooyoung@chungbuk.ac.kr

successful production. Even though most wind-pollinated crops show little problems in pollination, animal-pollinated crops often present limited level of pollination, particularly in intensive horticultural regions where heavy use of pesticide has decimated indigenous insect populations. The pollen spray will be a physical means of pollination to overcome pollen-transfer deficiencies and to increase crop production.

Harvested fruits and vegetables are highly perishable agricultural products. The major limiting factor in storage of fruits and vegetable is spoilage losses sustained during production, transportation and storage. Control of postharvest disease of fruits and vegetables relies mainly on the spray of chemical fungicide. In addition, the increased health consciousness or the safety of foods of consumers, diminished food preparation times have recently combined to increase the demand for minimally processed fruits and vege- bles. Minimal or light processing of fruits and vegetables describes processing steps such as trimming, peeling, sectioning, slicing, and corning. However, lightly processed produce has a greatly reduced shelf life compared to whole fruits and vegetables. Several techniques have been employed to minimize the deleterious effects of minimal processing, including refrigeration, controlled atmosphere packaging, use of additives, and edible coatings. Edible coatings can minimize undesirable changes due to minimal processing and also useful as carriers of additives, such as antioxidants, acidulants, fungicide and preservatives (Baldwin et al. 1995, 1996). In addition, the hollow cone misting and fogging nozzle can be used in a very wide range of applications where small droplets and their advantages of minimal wetting and rapid evaporative cooling are valued- poultry and livestock cooling, storage areas and warehouses, supermarket displays of fruit, vegetables and seafood. Spray drying may be included in the postharvest sprays, but this will not be discussed in this article.

The penalties of pesticide spray mentioned above require the alternative pest control method with competitive economics to chemical pesticides. Thus biopesticides are now being recognized as growing components in the crop-protection armory. It is estimated that the registered biopesticide products will be more than 100 by the end of the year 2000. Most formulation of biopesticide had been developed to facilitate application with conventional spraying apparatus, particularly nozzles.

As summarized, the liquid atomization technology in the field of agricultural spray is important in the pesticides sprays, pollen sprays, postharvest sprays and biological control agent sprays. Some might suggest the inclusion of spray drying in the postharvest sprays, although this is not covered in this article. The objective of this paper is to provide an overview of current status in the agricultural spray field, and future trends and needs will be presented.

Agrochemical Sprays

The sprayer in the pesticides application can be classified as the hand-held sprayers, boom sprayer, rotary sprayer, orchard sprayer and aerial sprayers, etc. The processes involved in agrochemical spray include pesticide selection and formulation, atomization, transport to target, evaporation, impaction on plant surfaces, deposition, movement in/on surface, and biological effect.

The flow and spray characteristics of agrochemical sprayer which will influence spray drift and deposition are strongly affected by the physical properties such as density, viscosity and surface tension of the selected pesticides formulation. Agrochemical spray liquids are generally much more complex since they frequently contain adjuvants such as notably surfactant, emulsifiable oils, and polymers as retention enhancers and the different kind of drift retardants (Tominack, 2000).

The most factors that are influenced by atomization of agrochemical spray are the spray drift, the quantity and distribution of the deposit on the target and the uptake or mode of action of the agrochemical at the target surface. Various nozzles and sprayers are using for the agrochemical spray in the greenhouse, orchard and fields etc. Thus it is important to define nozzle performance because of its ultimate effect on the efficacy of the agrochemical application process. The droplet size and velocity characteristics of liquid sheet emerged from flat fan nozzles were studied in a wind tunnel in the presence of a non-uniform cross-flow by Farooq et al.(2001). In addition, a numerical approach to relate the spray angle of a flat fan nozzle to its internal geometry was presented by Zhou et al.(1996).

The generalized theoretical and semi-theoretical equations for predicting the droplet size and velocity from pressure-swirl nozzle were suggested by Sidahmed (1996). The experimental data for the liquid sheet thickness and velocity are still required.

The evaporation of droplet released into the atmosphere is one important phenomena that must be understood when assessing the implications of the agricultural application of pesticides(Teske et al., 1998).

The transport of spray droplets to the plant is one of important processes in agrochemical sprays. The entrained air and droplet velocities produced by flat fan nozzles were investigated by Miller et al.(1996, No refer number). The existing empirical and theoretical transport model (Sidahmed, 1997) of spray droplets can not account for the entrainment of the surrounding air, drop-turbulence, evaporation, mutual interaction of the droplets in a spray such as collision and coalescence simultaneously. In particular, the existing models assume that a liquid jet breaks up immediately after leaving the nozzle and all droplet are formed at the nozzle tip. Therefore, the modification of existing models by introducing the expression for the breakup length of liquid sheet is required.

The outcome of droplet impaction on leaf surface is the retention and reflection. The degree of retention and reflection from leaf is a function of the condition of the incoming droplets, the configuration of the impacted surface and chemistry of surface functional groups of the target surface. The condition of the incoming droplets includes the physical properties of spray solution, typically surface tension and viscosity, spray pattern such as droplet size and velocity, and turbulence in plant canopy. The configuration of the impacted surfaces means the surface morphology including the degree of pubescence, venation and fine-structure (Spillman, 1984, Reichard, et al., 1986, Zhang and Basaran, 1997, Reichard et al., 1998).

Ground deposit of pesticides spray is a function of the canopy density which may be expressed in the leaf area index, the droplet trajectory and the capture efficiency(Gyldenkarne et al., 1999). However, only a few papers have been published evaluating the soil deposition.

The physicochemical properties of the plant cuticle influence the behaviour of spray droplets and, in turn, may affect the rate and efficiency of cuticle penetration(Kirkwood, 1999).

1. Droplet Size in Agrochemical Spray

The importance of droplet size in the agricultural application of pesticides are reviewed by Hewitt(1997, 8-17). This review article also includes a summary of international development of the importance of droplet size in agricultural spraying and measurement techniques for droplet size spectra. The most widely used parameter of droplet size in the agricultural spray is the volume median diameter(VMD) measured in micrometer(Matthew, 1992). A representative sample of droplets of a spray is divided into two equal parts by volume so that one half of the volume of the spray is in droplets larger than the value of the VMD, while the other half by volume is in smaller droplets. A few large droplets can account for a large proportion of the spray and so can increase the value of VMD, which on its own does not indicate the range of droplet sizes. This VMD, often expressed with $D_{v0.5}$ or $D_{0.5}$, is called as mass median diameter(MMD) by Lefebvre (1989), thus misleading the definition. The other widely used parameter of droplet size in the agricultural spray is the number median diameter (NMD). The NMD divide droplets into two equal parts by number without reference to this volume, thus emphasizing the small droplets.

The range of droplet size in the agricultural spray is usually expressed as VMD/NMD or span(relative span factor, relative diameter span factor). Because the value of VMD and NMD is affected by the proportion of large and small droplets, respectively, the ratio between these parameters is often an indication of the range of sizes, thus the more uniform the size of droplet the nearer is the ratio to 1. Sometimes the range of droplet size is expressed by the span in which the difference in the diameter for 90% and 10% of the spray by volume is divided by VMD($=(D_{0.9}-D_{0.1})/D_{0.5}$).

International Spray Classification System have been established on the basis of nozzle classification methods which use droplet size distribution from reference nozzles as standards to define spray quality categories such as very fine, fine, medium, coarse and very coarse(Southcombe et al., 1997). In ASAE

Standard X-572, extremely coarse is added in the spray quality categories(Womac, 2000).

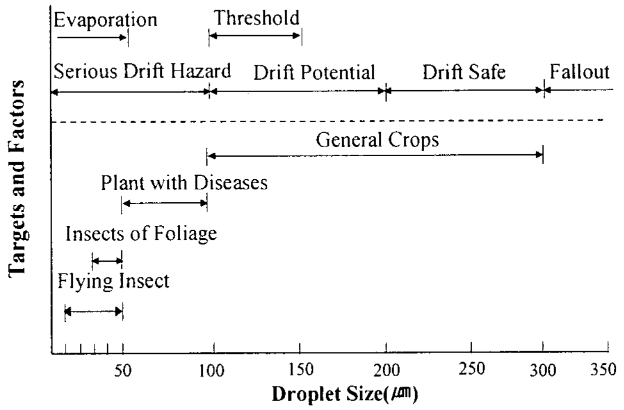

Fig. 1 Relationship between optimum droplet size ranges for selected targets and risk of drift.

One very important factor influencing drift is the size of the droplets sprayed. The relationship between optimum droplet size ranges for the selected targets and the risk of drift is shown in Fig. 1. As can be seen in Fig. 1, there is no single best droplet size to optimize the selected target and pests. Research has shown that for greenhouse pesticides spray, it is recommended to produce 30-60 μm VMD. For typical applications with boom type sprayers, droplets of 100 μm or less are considered highly to be driftable and droplets of 50 μm or less completely evaporate before reaching the target. Yates et al.(1995) had reported that for fan and cone nozzles in a wind tunnel test, drops smaller than 150 μm in diameter would generally pose the most serious drift hazard. Drop size in the range of 180 to 220 μm is recommended for the pesticide applications in orchards and fields in case of wind speed of 0.5 to 4 m/s. However, Chapple et al.(1997) suggested for flat fan nozzle that droplets with diameter less than 150 μm are prone to drift and that drops > 300 μm had a low probability of being retained intact by plant surfaces. As shown in Fig. 1, the droplet size distribution within a spray is a major factor influencing drift and that the percentage of spray volume in droplet sizes below a defined threshold is a good indicator of the risk of drift. This threshold has commonly been taken as around 100 μm (Miller, 1999, Piggott and Matthews, 1999). However, Walklate et al.(1994) suggested that the % volume of droplets with diameters less than 100 μm is not a good indicator of spray drift for agricultural boom sprayer applications. Thus, this will give misleading information when comparing the likely risk of drift from different nozzle types and/or when sprays have different velocity profiles, structures and entrained air profiles.

2. Increase of Deposition

The techniques to increase of deposition include the electrostatic based pesticide spray and spray with automatic techniques such as image analysis and optical sensors that are beyond of the scope of this article.

Electrospray : Electrostatic spraying of pesticides can improve not only the deposition efficiency, but also the spatial distribution of deposited droplet throughout the plant canopy, particularly underleaf where pests preferentially reside. This leads to significant advances in the research and development of electrostatic spraying technology for beneficial agricultural applications during the latter half of the 20th century. The application of electrostatic pesticides spraying covers the hand-held sprayers, tractor mounted systems such as boom sprayers and rotary sprayers, orchard sprayers and aerial sprayers(Chang et al., 1995).

Charging methods of pesticides include induction charging, ionised field charging(ionised-field corona-type charging), direct charging(contact charging), and combination charging of induction and ionised field charging. While the ionised filed charging method had shown limited promise for liquid pesticides, induction charging method gives more fully accomplishing results (Jahannama et al., 1999, Laryea and No, 2001, Laryea et al., 2001). In addition, Law (2001) had suggested that a hybrid aerodynamic-electrostatic spray system is most appropriate for outdoor trajection of charged-droplet clouds towards, and penetration into, three-dimensional plant canopies.

Factors affecting the deposition of electrostatic pesticide spray include electrical conductivity and permittivity of liquids, electrical field gradient between the atomizer and the plant, space charge, image charge etc. An interesting and important limitation to the effectiveness of electrostatic spraying can arise due to ionisation at the surfaces of some crops which have sharply pointed leaves or hairs(Bailey, 1988). This problem can be removed by introducing the bipolar spray charging technique(Cooper and Law, 1987).

Numerous experimental tests of electrostatic pesticides spraying technology by many researchers, both in the laboratory and the field, have generally verified 2-8 fold increases in deposition, as well as improved spatial distribution on plant surfaces, attributable to electrostatic forces(Law, 2001) However, there is a limitation that the droplet size should be of approximately 30-50 μm VMD in order to ensure electrostatic forces dominating gravity for droplet charge-to-mass ratio values greater than around 2mC/kg.

In addition to the application of electrostatic pesticide spraying, electrohydrodynamic atomization (EHDA) technique was applied to develop a multiple EHDA nozzle for the application of pesticide in the greenhouse(Geerse et al., 2000).

It should be pointed out here that there exists some difference between electrohydrodynamic spraying and electrostatic spraying. Electrohydrodynamic spraying is the case in which the production of droplets from a liquid is only due to the action of an electric field. Meanwhile, electrostatic spraying(electrospray) is the case in which a liquid is sprayed by pneumatic or other means and in which the application of an electric field has only the effect of charging the droplets and decreasing slightly their average size.

3. Reduction of Drift

The introduction of drift retardants into the formulations is one method of giving drift control by changing the physical properties of fluid sprayed. In addition, technical solutions by introducing the mechanical means have been developed. The nozzles with pre-orifice, air-assist, air inclusion, shield or shroud assist and pulse flow can be classified into the method for the reduction of drift.

(1) Drift retardants : Pesticide formulations contain the active ingredient plus other chemicals such as adjuvants and drift retardants. Adjuvants are commonly added to pesticide formulations to enhance pesticide performance by serving several purposes such as wetting and emulsifications(Bode et al., 1976, Butler Ellis, and Tuck, 1999). Many spray drift retardants have been used to reduce off-target drift and improve the efficacy and performance of pesticides on the intended targets by increasing the mean droplet size(Zhu et al. 1997, Reichard, D. L. et al., 1993). While there are many commercially available drift retardants, only a few retardant active ingredients such as polyvinyl, polyethylene oxide and polyacrylamide are often used in the formulation of drift retardants.

The physical properties of fluid such as viscosity, density and surface tension are well known to affect the spray drop size distribution from a nozzle. For fluids with viscoelastic properties which are often contributed by dissolved polymers as the drift retardants, extensional viscosity has been recognized as an important factor in droplet size distribution. It is known that polymeric drift retardants can remarkably increase the extensional viscosity, and to a lesser extent, the viscosity of solutions, but they have little effect on either surface tension or density. The importance of extensional viscosity has stimulated research in the field of measurement of extensional viscosity and correlations with droplet size distribution (Reichard & Zhu, 1996, Mansor & Chigier, 1995, Dexter, 1996, 2000).

(2) Low-drift nozzle : The use of a pre-orifice in a flat fan nozzle design has been developed to reduce drift by creating a coarser spray quality, in other words, by reducing the fraction of droplets below around 100 μm. Measurement of the droplet velocity profiles from low-drift nozzles show that droplets from this nozzle design travel more slowly than from a conventional flat fan design operating at the same pressures and flow rates(Miller 1999). The pre-orifice restrictor serves to reduce pressure and shifts the droplet spectrum towards larger droplets and reduces droplet velocity. The comparison of the effectiveness of low-drift nozzle without shield, which will be explained in the next section, with that of standard flat fan nozzles with a shield was carried out by Ozkan et al.(1997). The result showed that 0.61 ℓ/min standard fat fan nozzle with a certain shield was more effective to reduce spray drift than low-drift nozzle without a shield.

(3) Air assisted nozzle : Basic concepts of air-assisted ground crop spraying are to increase spray drop velocity and control their trajectory so that deposition on plants is improved by introducing the air and thus problems of spray drift and soil contamination are reduced. The main parameters for air-assisted sprayer are: air speed, air jet angle, airflow rate, and height of spray release above the target crop. According to the variation of air speed, leaf coverage for the top, middle, and bottom parts of the canopy is widely different(Panneton et al., 2000). A vertical oriented air flow is less effective for coverage and produces more soil deposition than forward or backward angling, forward angling being the most efficient(Hilsop and Western, 1993). In addition, optimum air jet angle is different with air speed. There are relatively little recent data to give the effects of application height above the crop on the risk of drift. In addition, no research on the effect of air assistance on the spray characteristics, especially droplet size, can be found in the literature.

(4) Air inclusion nozzle : Large droplet applications can significantly reduce the amount of drift but they can reduce deposition efficiency and pesticide effectiveness. However, the larger droplets from the air inclusion nozzles contain air bubbles within the droplets and burst on impact with the target. This improves the spread and adhesion of the pesticides which in turn allows the use of a coarser spray than usual which reduces drift and improves deposition efficiency. The air inclusion nozzles allow air to be mixed with liquid within the nozzle as the spray is produced, most commonly either by injecting air under pressure(twin fluid nozzle) or by drawing air in using a venturi mechanism(air induction nozzle).

In the twin fluid nozzle, liquid from the spray tank is fed onto the baffle plate where it breaks into droplets. These are forced into the swirl chamber where they are mixed with a separate flow of compressed air. The droplets are then swept past the baffle plate where they are deflected off the flood tip into a 100 degree fan onto the target(McDonald, 1990, Matthew, 1992). Some of the air is entrapped by the spray liquid to produce air-included droplets. The main use has been in the application of low volumes without too small an orifice liable to blockage. Spray drift from this nozzle was significantly lower than that obtained from flat fan nozzles. This twin fluid nozzle is not used at too higher air pressure than 1 MPa or very lower flow rates than 0.5 ℓ/min, otherwise drift could be exacerbated. The incident of air inclusions was estimated by collecting the spray from the twin fluid nozzle in a petri dish containing a 5 mm layer of silicon fluid topped by 8-10 mm of oil. The droplets were inspected using a binocular microscope illuminated with cold light source(Combellack et al., 1996).

In the air induction or air infusion nozzle, the liquid being sprayed passes through a tapered nozzle which accelerates the liquid and projects the flow into the tapered mouth of the venturi. This creates a vacuum which causes air to be sucked in through the slots in the periphery of chamber. The mixture of air and liquid is compressed at it passes through chamber and is then sprayed through a flat fan nozzle. As same as with the twin fluid nozzle, drift from this nozzle was considerably lower than that obtained from the conventional nozzle. However, the holes on the side of the nozzle can draw in dust that may be suspended in the air and resulted in any type of plugging of nozzle, thus the additional filter will be required. The comparison of droplet size and drift potential between conventional, low drift, and air induction nozzles were presented by Bendig(1999). However, as pointed out by Miller and Butler Ellis(2000), techniques for quantifying included air are not well developed and further work is required to enable the density of droplets to be determined in-flight to improve our understanding of the operation of these types of air induction nozzles.

(5) Shield or shroud assisted nozzle : The reduction of potential for drift has been accomplished by using some kind of shield or shroud to overcome the drift-producing air currents and turbulence that occur around the nozzle during spraying. Many researches had conducted both in the laboratory and field to quantify the effects of mechanical, pneumatic, porous, and solid shields on drift. Most of studies indicate that most of these device reduce off-target spray drift(Smith et al. 1982, Furness, 1991). However, the results vary remarkable from one study to another due to varying atmospheric conditions in the field experiment. Nine different shields tested by Ozkan et al.(1997) in a wind tunnel concluded that a double-foil shield produced the best deposition result. The shield assisted spraying technique have been considered as economically viable alternatives to expensive air-assisted sprayers.

The combined technology with shield assisted nozzle into electrospray had been investigated by Lake et al.(1982). They carried out the effect of a shield on the penetration of electrically charged and uncharged droplets into barely in the laboratory using real plants. Their results showed that there was more deposits on targets, both with charged and uncharged spray, when a shield was employed. However, they indicated that there was a problem with the charged spray being attracted to, and deposited on the shield.

The shielded system for orchard sprayer is called as the recycling air-assisted tunnel sprayer or shielded recycling sprayer. The most important advantage of this sprayer is an outstanding reduction of emission to the environment(50% by Doruchowski and Holownicki, 2000), considerable saving of chemicals(20-30% by Ade and Pezzi, 2001), and safety of operator, attributable to recycling capability and confinement of spray. However, the shielded recycling sprayer can be used only in dwarf and semi-dwarf orchard and are not readily adopted or modified for use on slopes and in multi-row systems.

(6) Pulse flow nozzle : As an another introduction method of mechanical means, pulse width modulation as an alternative to pressure variation for flow control was applied to reduce the drift by Giles et al.(2000). Their results suggested that droplet size spectrum can be maintained for adequate target coverage while droplet flight times can be reduced and deposition efficiencies improved.

Pollen Sprays

The degree of plant pollination achieved is important for the successful crop production in orchards, greenhouse and the fields. Most wind-induced crops reveal relatively less pollination problem than insect- pollination crops, as long as adequate pollinators are present and favorable weather occurs during flowering. Inset-pollinated crops often present severely limited levels of pollination due to the lack of adequate animals such as insects and honeybees.

Aerodynamic-electrostatic pollination technique is one of backup strategy to supplement and enhance natural pollination where required. When pollen grains are suspended in an appropriate conductive carrier liquid, they can be electrostatistically sprayed and deposited by induction spray-charging technology. The dispersion liquid also provides electrical continuity to earth from the droplet-formation region of the liquid film or jet as it is atomized from a continuum into a discrete droplet phase(Law et al. 2000).

Whereas the induction spray-charging technology is usually applied for liquid-dispersed pollen, corona-charging systems is introduced for dry pollen suspensions. Even though charged pollen depositions in laboratory scale studies for both dry pollen and liquid-dispersed pollen were remarkably increased than uncharged pollen one, the results under actual field conditions reveal that the optimization of biological and operational factors such as most receptive flower developmental stage for aerodynamic-electrostatic pollen application, pollen dosage, and number of applications, etc(Law, 2001).

Postharvest Sprays

Approximately 10-30% of harvested commodities is discarded due to various fungal and other micro-organisms which degrade the foodstuffs in storage and shipment. Control methods by chemical, biological and physical means are routinely used to reduce foodstuffs losses due to spoilage. Control of postharvest diseases of fruits and vegetables relies mainly on the spray of chemical fungicides. Aqueous solutions or suspensions of chemical fungicides are commonly sprayed by pressure nozzles onto the product at some stage along the processing or packing line prior to shipment. Such spray applications utilizing droplets of typically 300-600 μm volume median diameter are characterized by poor surface coverage, inefficient droplet deposition and excessive rebound and runoff of spray liquid. Recently, improvements had been done by introducing the air-assisted, induction charging electrostatic spray application method(Law and Cooper, 2000). However, the spray characteristics including drop size distribution were not conducted.

In food processing plants, electrohydrodynamic atomizing and charging nozzle is using for the enhanced surface coating efficiencies of food flavorings, sweetness, vitamin compounds etc.(Law, 2001). In addition, spray technology can be applied effectively to the edible coatings on meats, poultry and seafoods and the further research is required in this field(Gennadios, et al., 1997).

Biopesticides Sprays

Biological control agents or biopesticides has been obtaining increased interest and attention due to their inherent characteristics of environmentally friendly, safe to non-target organisms and integrated crop management(ICM)-compatible approaches and tactics for pest management. Biopesticides is a terminology that comprehends many aspects of pest control such as microbial(viral, bacterial and fungal) organisms, entomophagous nematodes, plant-derived pesticides (botanicals), secondary metabolites from micro-organisms (anti-biotics), insect pheromones applied for mating disruption, monitoring or lure-and-kill strategies, genes used to transform crops to express resistance to insect, fungal and viral attacks or to render them tolerant of herbicide application(Copping and Menn, 2000).

Even though biopesticides are now being recognized as growing components in the crop protection field, the biopesticide share in the world pesticide market is still around little more than 1% of the total world pesticide market. Most biopesticides are sold as wettable, dustable or dispersible powder, soluble concentrate and granular, emulsificable concentrate, and liquid formulations, and used as a spray. While a great deal of work has been undertaken on the production, viability and stability of biopesticides, but the atomization and spray characteristics of biopesticides are not being elucidated. The continued robust growth of the global biopesticide application will be possible with removing the obstacles such as limited shelf-life, high specificity and limited persistence in the environment, etc.

Future Research Challenges

Due to space limit, only a portion of research and development of agricultural spray application were reviewed. Likewise omitted have been significant advances of measurement techniques of droplet size and velocity, aerial spray and spray modelling, especially CFD code etc. Further research challenges in electrostatic crop spraying was summarized in detail by Law(2001).

It is not currently technically feasible to accurately deduce a measure of drift risk such as $< 100\ \mu m$ or $< 150\ \mu m$ in sprays with different structures, velocity profiles etc. In addition, a few researches on the droplet size of fallout can be found in the literature. In the pesticides spray, the researches on the measurement of liquid sheet thickness and breakup length of liquid sheet for hollow cone spray are essential to understand the atomization processes and to develop the transport model to target.

In the area of air-assisted spray technology to reduce drift, further works on the effect of application height on drift and air assistance on droplet size should be followed. In addition, methods for quantifying included air in the air inclusion techniques are required. The atomization characteristics of biopesticides spray are not being elucidated and the formulations of biopesticides should be taken into account the spray characteristics of existing nozzle and sprayer. A combined technology with electrostatic method into one of method for the reduction of drift may be an effective strategy for increasing deposition and reducing drift. Only an integrated approach involving all stakeholders such as engineers, chemists, and biologists, etc. can result in improved application of agricultural spray in the future.

References

Ade, G. and F. Pezzi. 2001. Results of Field Tests on a Recycling Air-Assisted Tunnel Sprayer in a Peach Orchard. J. Agric. Engng Res. 80(2):147-152.

Bailey, A. G. 1988. Electrostatic Spraying of Liquids, Research Studies Press.

Baldwin, E. A., M. O. Nisperos-Carriedo and R. A. Baker. 1995. Edible Coatings for Lightly Processed Fruits and Vegetables. HortScience. 30(1):35-38.

Baldwin, E. A., M. O. Nisperos-Carriedo, X. Chen and R. D. Hagenmaier. 1996. Improving storage life of cut apple and potato with edible coating. Postharvest Biology and Technology. 9:151-163.

Bendig, L. 1999. Crop Protection Nozzles and Spray Drift Overview and New Developments. In Proc. 16th ILASS-Europe, Toulouse, 5-7 July 1999, 7-12.

Bode, L. E., B. J. Butler and C. E. Goering. 1976. Spray Drift and Recovery As Affected by Spray Thicker, Nozzle Type, and Nozzle Pressure. Transactions of the ASAE. 19(2):213-218.

Butler Ellis, M. C. and C. R. Tuck. 1999. How adjuvants influence spray formation with different hydraulic nozzle. Crop Protection 18:101-109.

Chang, J. S., A. J. Kelly and J. M. Crowley. 1995. Handbook of Electrostatic Processes, Marcel Dekker, Inc.

Chapple, A. C., T. M. Wolf, R. A. Sowner, R. A. J. Taylor and F. R. Hall. 1997. Use of nozzle-induced air-entrainment to reduce active ingredient requirements for pest control. Crop Protection. 16(4):323-330.

Combellack, J. H., N. M. Western and R. G. Richardson. 1996. A Comparison of the drift potential of a novel twin fluid nozzle with conventional low volume flat fan nozzles when using a range of adjuvants. Crop Protection. 15(2): 147-152.

Copping, L. G. and J. J. Menn. 2000. Biopesticides: a review of their action, applications and efficacy. Pest Manag. Sci. 56:65-676.

Cooper, C. and S. E. Law. 1987. Bipolar spray charging for leaf-tip corona reduction by space-charge control. IEEE Trans. IA-23(2):217-223.

Dexter, R. W. 1996. Measurement of Extensional Viscosity of Polymer Solutions and Its Effects on Atomization from a Spray Nozzle. Atomization and Sprays. 6:167-191.

Dexter, R. W. 2000. Emulsion Properties and Agricultural Spray Quality. In Proc. 8th ICLASS, Pasadena, USA, July 2000, 341-348

Doruchowski, G. and R. Holownicki. 2000. Environmentally friendly spray techniques for tree crops. Crop Protection. 19:617-622.

Farooq. M., R. Balachandar, D. Wulfsohn and T. M. Wolf. 2001. Agricultural Sprays in Cross-flow and Drift. J. Agric. Engng Res. 78(4):347-358.

Furness, G. O. 1991. A Comparison of a Simple Bulff Plate and Axial Fans for Air-Assisted, High-Speed, Low Volume Spray Applications to Wheat and Sunflower Plants. J. Agric. Engng Res. 48:57-75.

Geerse, K. B., J. C. M. Marijnissen, B. Scarlett, A. Kerssies, M. Van der Staaij and C. A. van der Meer. 2000. A multiple EHDA nozzle system for the spraying and selective deposition of pesticides in greenhouse. In Proc. 8th ICLASS, Pasadena, USA, July 2000, 359-364.

Gennadios, A., M. A. Hanna and L. B. Kurth. 1997. Application of Edible Coatings on Meats, Poultry and Seafoods: A Review, Lebensem-Wiss.u.-Technol. 30:337-350.

Giles, D. K., P. G. Andersen and M. Nilars. 2000. Using Pulsed Sprays from Oversized Orifices to Increase Momentum and Kinetic Energy in Depositing Agricultural Sprays. In Proc. 8th ICLASS, Pasadena, USA, July 2000, 354-358.

Gyldenkarne, S. Bo, J. M. Secher and E. Nordbo, 1999. Ground deposit of pesticides in relation to the cereal canopy density. Pestic. Sci. 55, 1210-1216.

Hewitt, A. 1997. Droplet Size and Agricultural Spraying, Part I: Atomization, Spray Transport, Deposition, Drift, and Droplet Size Measurement Techniques. Atomization and Sprays. 7:235-244.

Hislop, E. C. 1987. Can we define and achieve optimum pesticide deposits? Aspects of Applied Biology. 14:153-172.

Hilsop, E. C. and N. Western. 1993. Air-Assisted Spraying of Cereal Plants under Controlled Conditions. In Proc. ANPP-BCPC 2nd Int'l Symp. on Pesticide Application Techniques, 22-24 Sept. 1993, Strasbourg, UK.

Jahannama, M. R., A. P. Watkins and A. J. Yule. 1999. Examination of Electrostatically Charged Sprays for Agricultural Spraying Applications. In Proc. 16th ILASS-Europe, Toulouse, 5-7 July 1999, 13-18.

Kirkwood, R. C. 1999. Recent developments in our understanding of the plant cuticle as a barrier to the foliar uptake of pesticides. Pesticide Science. 55:69-77.

Lake, J. R., R. Green, M. Tofts and A. J. Dix. 1982. The effect of an aerofoil on the penetration of charged spray into barley. British Crop Protection Conference-Weeds. 1009-1016.

Laryea, G. N. and S. Y. No. 2001. Evaluation of Charged and Uncharged Spray Deposition Characteristics on Plant Canopy, In Proc. 17th ILASS-Europe, Zurich 2-6 Sept. 2001.

Laryea, G. N., T. G. Kang and S. Y. No. 2001. Spray Characteristics of Electrostatic Pressure-Swirl Nozzle, In Proc. 6th ILASS-Asia, Busan, Korea, 11-13 Oct. 2001, 223-228.

Law, S. E. 2001. Agricultural electrostatic spray application: a review of significant research and development during the 20th century. Journal of Electrostatics. 51-52:25-42.

Law, S. E. and S. C. Cooper. 2000. Air-Assisted Sprays for Postharvest Control of Furit and Vegetable Spoilage Micororganisms, IEEE/IAS Conference record, Rome: 796-801.

Law, S. E., H. Y. Wetzsten, S. Banerjee and D. Eisikowitch. 2000. Electrostatic Application of Pollen Sprays: Effects of Charging Field Intensity and Aerodynamic Shear Upon Deposition and Genrminability. IEEE Trans. IA-36(4):998-1009.

Lefebvre, A. H. 1989. Atomization and Sprays, Hemisphere Pub. Co.

Mansour, A. and N. Chigier. 1995. Air-blast atomisation of Non-newtonian Liquids, J. Non-Newtonian Fluid Mech. 58:161-194.

Matthew, G. A. 1992. Pesticide Application Methods, 2nd ed., Longman Scientific & Technical.

McDonald, D. 1990. Sprayers and accessories at Smith-field. International Pest Control. 32(1):6-9.

Miller, P. C. H. 1999. Factors influencing the risk of drift into field boundaries, The 1999 Brighton Conference-Weeds, 5B-1:439-446.

Miller, P. C. H. and M. C. Butler Ellis. 2000. Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. Crop Protection. 19:609-615.

Miller, P. C. H., M. C. Butler Ellis and C. R. Tuck. 1996. Entrained Air and Droplet Velocities Produced by Agricultural Flat-fan Nozzles. Atomization and Sprays. 6:693-707.

Ozkan, H. E., A. Miralles, C. Sinfort, H. Zhu and R. D. Fox. 1997. Shields to Reduce Spray Drift. J. Agric. Engng Res. 67:311-322.

Panneton, B., H. Philion, R. Theriault and M. Khelifi. 2000. Spray Chamber Evaluation of Air-Assisted Spraying on Potato Plants. Transactions of ASAE. 43(3):529-534.

Piggott, S. and G. A. Matthews. 1999. Air induction nozzles: a solution to spray drift?, International Pest Control. Jan/Feb: 24-28.

Reichard, D. L. and H. Zhu. 1996. A System to Measure Viscosities of Spray Mixtures at High Shear Rates. Pesticide Science. 47:137-143.

Reichard, D. L., H. Zhu, R. A. Downer, R. D. Fox, R. D. Brazee, H. E. Ozkan and F. R. Hall. 1996. A System to Evaluate Shear Effects on Spray Drift Retardant Performance. Transactions of the ASAE. 39(6):1993-1999.

Reichard, D. L., R. D. Braze, M. J. Bukovac and R. D. Fox. 1986 A System for Photographically Studying Droplet Impaction on Leaf Surfaces. Transactions of ASAE. 29(3):707-712.

Reichard, D. L., J. A. Cooper, M. J. Bukovac and R. D. Fox. 1998. Using a Videographic System to Assess Spray Droplet Impaction and Reflection from Leaf and Artificial Surfaces. Pesticide Science. 53:291-299.

Sidahmed, M. M. 1996. A Theory for Predicting the Size and Velocity of Droplets from Pressure Nozzles. Transactions of the ASAE. 39(2):385-391.

Sidahmed, M. M. 1997. A Transport Model for near Nozzle Fan Sprays. Transactions of the ASAE. 40(3):547-554.

Smith, D. B., F. D. Harris and B. J. Butler. 1982. Shieled Sprayer Boom to Reduce Drift. Transactions of the ASAE. 25(5):1136-1140.

Southcombe, E. S. E., P. C. H. Miller, H. Ganzelmeier, J. C. van de Zande, A. Miralles and A. J. Hewitt. 1997. The International(BCPC) Spray Classification System including a drift potential factor. In Proc. The 1997 Brighton Crop Protection Conference-Weeds, Brighton, U.K., 371-380.

Spillman, J. J. 1984. Spray Impaction, Retention and Adhesion: an Introduction to Basic Characteristics. Pesticide Science. 15:97-106.

Teske, M. E., C. G. Hermansky and C. M. Riley. 1998. Evaporation Rates of Agricultural Spray Material at Low Relative Wind Speeds. Atomization and Sprays, 8:471-478.

Tominack, R. L. 2000. Herbicide Formulations. J. Toxicol Clin Toxicol. 38(2):129-135.

Walklate, P. J., P. C. H. Miller, M. Rubbis and C. R. Tuck. 1994. Agricultural Nozzle Design for Spray Drift Reduction. In Proc. 6th ICLASS, Rouen, France, 851-858.

Wormac, A. R. 2000. Quality Control of Standardized Reference Spray Nozzles. Transactions of the ASAE. 43(1):47-56.

Yates, W. E., R. E. Cowden and N. B. Akesson. 1985. Drop Size Spectra from Nozzles in High Speed Air Stream. Transactions of the ASAE: 405-410.

Zhang, X. and O. A. Basaran. 1997. Dynamic Surface Tension Effects in Impact of a Drop with a Solid Surface. J. of Colloid and Interface Science. 187: 166-178.

Zhou, Q., P. C. H. Miller, P. J. Walklate and N. H. Thomas. 1996. Prediction of Spray Angle from Flat Fan Nozzles. J. Agric. Engng Res. 64:139-148.

Zhu, H., R. W. Dexter, R. D. Fox, D. L. Reichard, R. D. Brazee and H. E. Ozkan. 1997. Effect of Polymer Composition and Viscosity on Droplet Size of Recirculated Spray Solutions. J. Agric. Engng Res. 67:35-45.