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Improved systems of pesticide application

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More efficient transfer of pesticides to their intended biological targets is essential to reduce costs, to minimize the selection of resistant pests and to avoid environmental pollution. Most pesticide formulations are diluted in water and applied as sprays with a wide range of droplet sizes. The hazard of down-wind 'drift' of the smallest droplets is increased by evaporation, while most wastage is due to the largest droplets, which are poorly retained on most targets. Spray retention is improved by using narrower droplet-size spectra appropriate for particular targets. This permits reduction of spray volumes, use of less volatile formulations and more rapid and timely application in relation to pest infestations. Increased deposition on undersurfaces of leaves is achieved by controlling trajectories of electrostatically charged droplets. New low-energy systems to deliver ultra-low volumes of charged sprays will improve integration of chemical with biological controls and will eliminate hazards associated with preparation of sprays.

Introduction

Pesticide application is most inefficient under practical conditions. Sometimes over 99% of the pesticide fails to reach the intended target. Graham-Bryce (1977) calculated that as little as 0.02% of the dose of an insecticide applied was needed to control an insect in foliage, but when plants are the target, for example when applying a herbicide spray, up to 30% of the chemical may be utilized. These enormous losses occur at different stages during the complex multistage process of transferring a pesticide from the manufacturer's container to its site of action at the biological target (table 1).

The most widespread system of application involves the production of a concentrate, diluted in water by the user and pumped under pressure through an orifice to produce a polydisperse spray. Changes in droplet size as a result of evaporation, and differential movement of the droplets due to effects of gravity, wind velocity and air turbulence, result in considerable losses of pesticide between the nozzle and the intended target. Other losses are incurred owing to differences in collection efficiency of intended targets as diverse as an insect, fungal spore, leaf or the soil, to formation of deposits and subsequent movement of a pesticide into or over a surface and to the biochemical target, for example anticholinesterase action. The positioning of a nozzle relative to the target and its transportation through crops are additional factors that may reduce the efficiency of utilization of pesticides.

When an infestation occurs in a crop, farmers may spend less than half of the time they may devote to control measures actually spraying, the remainder being needed for transport of water and mixing the pesticides (Rutherford 1976). As wet soil and windy conditions reduce the number of days suitable for spraying, considerable crop loss may have been suffered before the farmer can complete a spray cycle through his entire crop.

Spraying diluted pesticides through hydraulic nozzles has developed over the last 100 years

11-2

and the treatments have effectively reduced pest populations, but the increased costs of energy required to manufacture and distribute pesticides and a general concern for environmental quality demand changes in conventional systems of application to reduce wastage and harmful side effects.

The improvement of pesticide application depends on a greater understanding of the production of spray droplets and their subsequent movement to the intended biological target.

TABLE 1. STAGES IN TRANSFER OF PESTICIDE TO A BIOLOGICAL TARGET

route	losses
concentrate sold to user	spillage degradation within container
diluted to spray mix	contaminated containers, incorrect mixing degradation in water
pumped to nozzle	leakage, blockages
production of spray droplets	erosion of nozzle increases output
movement of spray to target	‘drift’ to non-target organisms outside and within treated areas
deposition/distribution on target	failure to impact, degradation, weathering, volatilization
movement to site of action	poor uptake, excretion, adsorption
activity: biological response	metabolized

NOZZLE DESIGN

Hydraulic sprayers

The sheet of liquid produced from hydraulic nozzles disintegrates into filaments and then to droplets of widely differing sizes (Fraser 1958) (table 2). Changes in pressure affect the mean size, but the use of low pressure to reduce the number of aerosol droplets (smaller than 50 μm) liable to drift to neighbouring areas can produce some very large droplets, which may bounce off foliage. Attempts to restrict the range of droplets produced by hydraulic nozzles have included changes in orifice design to reduce the velocity of the spray, heating the liquid sheet so that it disintegrates closer to the nozzle (Dombrowski 1975), and adding chemicals to change the viscosity of the liquid. A significant reduction in the droplet-size spectra has been more easily obtained by using centrifugal or electrodynamic energy.

Centrifugal energy nozzles

The size of droplets thrown from the edge of a disc rotating at speed is inversely proportional to the angular velocity (Walton & Prewett 1949) but is also affected by flow rate. At low flow rates, droplets are produced singly but as flow rate is increased at the same disc speed, ligaments form with smaller droplets and satellites. During the transition from single to ligament droplet production the size spectrum is wider; then, as flow rate continues to increase, ligaments are thicker and larger droplets are obtained until the flow rate is so great that ligaments merge to form a sheet. As disc speed is increased, the flow rate suitable for either single or ligament droplet production is reduced. Separation of individual ligaments has been improved by grooves that individually feed teeth around the disc circumference, and reduce slippage of liquid over the disc surface. As there is a maximum flow rate for any particular disc design, multiple discs are sometimes mounted on a common shaft to accommodate higher flow rates needed when the transporting equipment is travelling faster along the ground. Alternatively on a large cone-shaped ‘disc’, deeper grooves have allowed increased flow rates at slow speeds, but at higher disc speeds the secondary break-up of the ligaments caused by friction with the surrounding air produced a wider droplet spectrum (Heijne 1978). The spray liquid can be charged electrostatically on the disc (Arnold & Pye 1980).

Table 2. Droplet sizes produced by various nozzles (Heijne 1978; Endacott 1980)

(Droplet sizes were measured with a laser light diffraction system.)

type	output l/min	pressure kPa	v.m.d. µm	v.m.d.:n.m.d.†
hydraulic nozzles				
fan	1.1	300	250	22.7
low-pressure fan	0.6	100	325	5.2
		rotational speed rev/min		
centrifugal				
spinning disc (12 cm diam.)	1	2000	262	1.5
	0.1	5000	94	1.4
		applied voltage kV		
electrodynamic				
‘electrodyn’	0.01	25	63	1.02

† V.m.d., volume median diameter; n.m.d., number median diameter. A v.m.d./n.m.d. ratio close to 1 indicates a narrow spectrum.

Electrodynamic nozzles

Spray liquid with a resistivity in the semiconducting range up to 10^8 Ωm is electrically charged when metered through a narrow gap in the spray head at a potential of the order of 15–25 kV, in close proximity to a field intensifying or counter-electrode connected to earth. The emerging liquid is charged with the same polarity as the spray head and is subjected to an intense divergent electrical field. This causes the surface of the liquid to form standing waves and from each crest a ligament is produced. The instability caused by the electric forces causes ligaments to break up into main and satellite droplets. Their initial trajectories are distinct owing to the effect of the electrical field on droplets of similar charge:mass ratios but different mass. Some satellite droplets are collected on the counter-electrode. The number of ligaments increases with voltage and decreases with flow rate, and conversely the thickness of ligaments is inversely related to voltage and increased by flow rate. The uniformity of the ligaments results in a very narrow droplet-size spectrum. This unique nozzle described by Coffee (1979) requires no mechanical energy and so has the advantage of having no moving parts and requiring very little energy. Annular and linear gaps in the spray head provide spray patterns suitable for different targets.

DROPLET MOVEMENT TOWARDS THE TARGET

Spray is normally projected into crop canopies from hydraulic nozzles held at close range (less than 0.6 m). Sometimes an air stream is provided to convey droplets upwards and over greater distances, as in some tree crop spraying. The smaller droplets are readily diverted by the wind, and with evaporation they can rapidly become very small particles of concentrated chemical. Farmers have been advised to avoid spraying when the wind is too strong, to reduce the effects of drift, particularly if susceptible crops are in adjacent fields downwind when herbicides are sprayed or if the pesticide is liable to harm bees active in flowering crops. Precise recommendations are difficult to give owing to local factors such as the topography of the area, but spraying should generally stop if the wind speed exceeds about 2.5 m/s at 0.5 m, which corresponds roughly to a wind speed of 5 m/s at 10 m (Adams 1978).

TABLE 3. PROPORTION OF SPRAY (PERCENTAGES) ON COTTON LEAVES AND THE SOIL SURFACE FOLLOWING APPLICATION OF CARBARYL BY KNAPSACK AND HELICOPTER SPRAYERS

	knapsack	helicopter
top of plants	27	54
middle of canopy	23	17
lower leaves	13	6
soil surface under plants	37	23

Knapsack was fitted with a tailboom so nozzles were placed between the rows, Y3 nozzles with v.m.d. = 150 μm; D6-25 cone nozzles with v.m.d. = 450 μm were used on helicopter. Plant height was approximately 0.8 m. (From Johnstone & Matthews (1965).)

Sedimentation of the largest droplets (more than 300 μm) falling at more than 1.5 m/s gives heavy deposition on the upper leaves and penetration through the crop canopy (table 3). The latter accounts for the greatest amount of chemical wastage and contaminates the habitats of spiders, ants and other beneficial species. Thus the largest and smallest droplets produced by a hydraulic nozzle are both potentially harmful.

Turbulent transport

The fear of long-distance 'drift' is based on the theory that the distance that droplets travel is proportional to their height of release and wind speed and is inversely related to their terminal velocity, the smallest droplets travelling further in strong winds and when released at a great height. When some herbicides are applied with a conventional tractor sprayer, serious damage may occur to crops up to 200 m downwind (Byass & Lake 1977). In practice, airflow is not laminar but turbulent owing to various factors including crop friction, and this results in a greater deposition of small droplets in crop canopies close to the release point than occurs in a ploughed field (Bache 1975; Lawson & Uk 1979), provided that they are not too small or have insufficient momentum to impact on foliage. The distribution of such droplets within a canopy may be similar to that of airborne insects and fungal spores.

The effective use of turbulent transport requires a narrower droplet-size spectrum than achieved with the hydraulic nozzle, to avoid wasteful sedimentation of the larger droplets on the nearest horizontal surface. Less-volatile spray formulations are also needed to prevent the small droplets from becoming too small for impaction in the canopy. Mineral and vegetable oils, molasses and other additives have been used to reduce the effect of evaporation when applying formulations diluted in water, as very few pesticides have been specially formulated for ultra-low volume application.

The main disadvantage of turbulent transport is that deposition is essentially on the windward surfaces of plants. The application of translaminar, systemic, translocated or volatile pesticides, or a reliance on subsequent redistribution of surface deposits, enable control to be achieved with many pesticides although coverage may be inadequate initially on the relevant plant surfaces; thus coverage of the undersurfaces of leaves will be poor unless air turbulence is sufficient to cause leaves to flutter.

Droplet trajectory control

There is considerable interest in using electrostatic forces to overcome the disadvantages of depending on air movement and sedimentation. An electric field between a charged nozzle and the nearest earthed object, the crop, induces an opposite charge on the foliage and this in turn attracts the droplets, which travel at a high velocity towards it. Coffee (1979) calculated that a 100 μm droplet would achieve a velocity of the order of 10 m/s when propelled by an electric field of 60 kV/m, compared with a terminal velocity of less than 2 m/s with an uncharged 250 μm droplet. As all the spray droplets have a similar charge, there is a dynamic interaction, which results in individual droplets' repelling each other to expand the cloud. The droplets travel along curved trajectories and can reach less exposed foliage, so the coverage of both under and upper surfaces of leaves can be obtained. Unfortunately, penetration is not very good in dense canopies as the large surface area nearest to the nozzle will collect most of the spray, particularly when the electric field is strong. In this situation the nozzle may have to be placed within the canopy as with uncharged sprays, or an airstream provided to propel the charged droplets into a canopy. Droplets generated electrodynamically can be, partially discharged by positioning a point in the region of high space–charge density and this enables greater use of natural air movement to disperse the spray.

The use of charged and uncharged droplets in different crop canopies requires further study to establish which size of droplet and charge:mass ratio is desirable to project the spray where it is needed. There is now the possibility of applying pesticides with smaller droplets and using electric fields to provide greater control of their trajectories even in windy conditions, to localize deposition where it is most needed and to minimize contamination of non-target organisms (Matthews 1980). Improved deposition on crop canopies can reduce the initial wastage of pesticides in the environment and particularly at soil level (Jones & Hopkinson 1979). This allows a greater survival of non-target species such as natural enemies and consequently the better integration of chemical and biological controls. In small-plot experiments, Pardede (1980) obtained an 88% reduction of *Plutella* larvae on brussels sprouts treated with 15 g/ha cypermethrin applied with an 'Electrodyn', but all the survivors were parasitized. The high-volume treatment with 45 g/ha gave a 100% reduction of larvae. Untreated larvae on potted plants placed in the sprayed area were only 40% parasitized compared with continued 100% parasitism in the 'Electrodyn'-treated plots.

Deposition on targets

Relatively few studies on the effect of different droplet sizes on biological efficacy have been made, owing to the wide range of droplet sizes in most sprays and the complexity of the different target surfaces that are sprayed. Brunskill (1956) showed that spray retention on a surface that is difficult to wet, such as pea leaves, could be improved by decreasing the surface tension of the spray, droplet diameter and the angle of incidence. Large droplets (greater than

150 μm) have sufficient kinetic energy to bounce off leaves, or may shatter on impact (Hartley & Brunskill 1958). Retention of 100 μm droplets of water plus surfactant on young barley leaves was very much greater than when droplets 200 μm or larger were applied (Lake 1977) but differential retention between crop and weed may be achieved more effectively with large drops (350 μm); thus more was retained on radish compared with barley with this size (Merritt 1980).

Droplets smaller than 100 μm are also more effectively collected by insects, whether flying or resting on plant surfaces, as indicated by studies on mosquitoes (Latta *et al.* 1947), tsetse flies (Hadaway & Barlow 1965) and locusts (Kennedy *et al.* 1948).

Aerial application of an involatile formulation of fenitrothion in butyl dioxitol at 1 l/ha gave a threefold increase in the amount of chemical recovered in dead *Panolis* larvae compared with the use of the same dosage as an emulsifiable concentrate diluted in water and applied at 20 l/ha (Joyce & Beaumont 1979). Deposits with a formulation containing only 10% involatile material were 1.6 times greater than a formulation with only 1.4% involatile material (Yates *et al.* 1967).

In laboratory tests with small droplets (less than 30 μm), Law (1980) obtained an up to sevenfold increase in deposition with charged sprays, while Arnold & Pye (1980) have reported improved deposition with decreased droplet size as the voltage was increased. With an electrodynamic sprayer, the recovery of charged droplets at *ca.* 80 μm was at least twice to four times that of uncharged droplets on cotton (Morton 1979).

Movement to the site of action

The chemical and physical properties of a pesticide and its formulation, as well as the characteristics of the substrate, clearly affect the subsequent biological activity of a spray deposit.

Malathion applied in small droplets (100 μm) penetrated the leaf cuticle faster, and less was washed off by rain compared with deposits from larger droplets (600 μm) (Polles & Vinson 1969), so with more efficient deposition, residues after ultra-low volume sprays are often higher unless the mass application rate is reduced.

However, the redistribution of surface deposits after application, particularly by rain, is sometimes very important. The control of some diseases is improved when spores and fungicide are washed to the same sites even by relatively small amounts of rain or leaf wetness (Courshee 1980; Hislop 1970). Also, the local movement of vapour is probably advantageous in modifying the biocidal range of individual droplets, but little information is available (Hislop & Baines 1980). In contrast, the downwind movement of 2,4-D vapour over greater distances is undoubtedly a cause of phytotoxic effects (Maybank *et al.* 1974).

The subsequent movement of a pesticide to its biochemical site of action is beyond the scope of this paper, but in the development of new systems of application, formulations must be designed to optimize biological activity: too great a concentration of active ingredient or surfactants can decrease the performance of a pesticide. Local scorching and reduction of uptake has been reported for some formulations of herbicides and suggests that the concentration of surfactant needs to match the application rate (Merritt 1980).

Biological response

It is only possible to give a few examples of the application of pesticides to foliage. Studies with the use of small droplets on leaf surfaces have indicated complex interactions between droplet size, the number of droplets per unit area and concentration of active ingredient in each droplet.

Insecticide application

Reay & Ford (1977) obtained greater mortality of *Spodoptera littoralis* with permethrin on cabbage leaves when using 83 μm compared with 123 and 164 μm droplets applying the same mass application rate and same droplet density. Similarly, Hadaway *et al.* (1978) showed that deposits of deltamethrin were more effective in 80 μm than 140 μm droplets when applied at 2.5 g/l and 0.156 l/ha against *Glossina austeni*. Two and a half times more 160 μm droplets were required to achieve the same level of control of *Laspeyresia pomonella* compared with 350 μm droplets, but with one-fifth of the deposit (Fisher & Menzies 1979). Other recent studies (unpublished) have indicated that on leaves droplets less than 80 μm diameter are more effective if they are deposited at the site of the pest. The improved deposition of small droplets and reduced wastage of chemical with charged sprays suggest that effective control should be obtained with lower dosages or better control with similar application rates compared with those used in conventional high-volume spraying.

Table 4. Comparison of cypermethrin applied electrodynamically at two rates with an uncharged spray applied above cotton plants to assess control of *Bemisia* (Morton 1979)

	application rate		numbers of whitefly adults per leaf	
	g a.i./ha	l/ha	4 days after spraying	15 days after spraying
‘Electrodyn’	50	2	2.8 b	8.0 b
‘Electrodyn’	16	0.63	2.1 b	10.3 b
hydraulic nozzle	60	20	8.5 a	11.5 ab
untreated	—	—	8.8 a	23.7 a

Values followed by the same letter are not significantly different at the 5% level.

Control of *Bemisia tabaci* on cotton was better (table 4) with a cypermethrin formulation applied electrodynamically compared with a simulated aerial spray (Morton 1979). Increased underleaf coverage was probably the major factor of achieving control with lower rates of application. Endacott (1980), using 50 g/ha pirimicarb, obtained a similar reduction of *Sitobium avenae* on the top of wheat plants to that obtained with 200 g/ha applied with a knapsack sprayer using 80 times the volume of spray.

Herbicide application

The smallest droplet size used in tests with barban applied to *Avena fatua* L., namely 110 μm, was the most effective (Lake & Taylor 1974), but so far no detailed examination of herbicides with droplets smaller than 100 μm has been considered. Phillips *et al.* (1980) reported that the best weed control in field trials was achieved with treatments giving more droplets per unit area, either by reducing droplet size to 135 μm or increasing the volume to 60 l/ha. The potential for using charged droplets smaller than 100 μm with less risk of drift now needs to be fully examined.

Application systems

The farmer has to bring together all the individual stages into a complete system of applying pesticides that coordinates with his other farming operations. The cost of wastage of expensive crop protection chemicals with the present systems of application and losses of crops as a consequence of late treatments, when wet soil, wind, rain or other factors delay access to fields, will be increasingly unacceptable. Another consideration is that many of the accidents with pesticides occur during dilution of the concentrated formulation, and this has led to the development of closed mixing systems (Brazzelton & Akesson 1975).

Costs and safety must therefore be fundamental considerations in the development of new systems of application relevant to modern crop production methods, but the main impetus to new developments has so far come from the less developed countries where a lack of water has been the main stimulus to the introduction of ultra-low volume application.

When the hand-held spinning disc sprayers were introduced, the original intention of the manufacturers was that pesticides appropriately formulated would be supplied in a screw-on litre container, so that mistakes due to incorrect mixing would be eliminated. However, the cost of supplying individual bottles was such that farmers preferred to refill the bottle from a larger can, or use cheaper formulations diluted with less water. Small sachets of wettable powder (Mowlam *et al.* 1975) have been diluted in 1 l of water for spinning disc sprayers. The provision of sachets was undoubtedly a major factor in the successful introduction of insecticide usage on cotton in central Africa. This method of packaging will no doubt increase in importance for the distribution of pesticides, especially wettable powders, which are exceedingly difficult to measure out in the field.

When more than 2 l/ha of formulated product is needed, the cost of transport to individual farms is greater than the equivalent cost of a concentrated wettable powder or emulsifiable concentrate to be diluted at the time of application. Any new system involving special formulation will therefore require ideally less than 1 l/ha of product.

The use of small charged droplets makes spraying with as little as 0.5 l/ha possible, and this reopens the potential for containers that fit the sprayer directly so that the farmer does not have to mix or transfer the chemical to a spray tank. This is a feature of the 'Bozzle' container concept for electrodynamic sprayers (Coffee 1981).

This closed system eliminates the problem of mixing, and by incorporating a plastic nozzle into the bottle opening ensures that the output and droplet size characteristics of the spray can be properly matched to the pesticide formulation. Also the 'Bozzle' provides a fresh nozzle each time and thus avoids the problems caused by erosion of the nozzle tip. The risk that empty containers will be a source of pollution can be reduced by a financial incentive to return it either for refilling at a central store or for recycling. The use of a small returnable tank or 'pallet' loads that plug into the sprayer will provide a similar system on larger farms where tractor-mounted equipment is currently in use.

The great reduction in weight by using very much lower volumes of spray eliminates the need for a tractor designed for draught work. A major new opportunity exists for a lightweight high-speed vehicle (Elliott 1980; Rutherford 1980) with low-pressure types for operation on certain soils, a very stable boom (Nation 1980) and sufficient clearance to minimize damage to crops such as wheat.

Higher operational speeds, up to 20 km/h, are necessary for improved timeliness of application to integrate chemical control with monitoring systems (Lewis, this symposium). The most successful use of lower dosages will only be achieved if infestations are checked rapidly over the entire area occupied by the pest population.

Conclusions

Pesticides will remain one of the important tools in pest management programmes, but greater emphasis will be given to the technology and management of pesticide application to use less energy to distribute smaller quantities of active ingredient and thereby reduce wastage and decrease harmful side effects. Controlled droplet application and electrostatic spraying will therefore play an increasingly important role in pest management programmes. So far the agrochemical industry has been reluctant to register new formulations specially for controlled droplet application, but the development of more active or more sophisticated chemical agents will provide an incentive for the use of new application techniques. These will be used for the application of conventional pesticides and also of growth regulating agents and for the control of pathogens.

New, more target-specific systems of application will tolerate less error, particularly when reduced volumes of spray are applied at a higher concentration and a lower dosage is applied to regulate pest numbers rather than aiming at complete kill. In contrast to existing hydraulic spraying equipment, technicians with quite different skills will be required to operate and maintain sprayers of the future, but the aim is to provide the user with a simpler application system to operate, thus transferring the complexity from the user to the producer. Already this trend is evident with the introduction of electronic controls and the screw-on 'Bozzle' concept. Training will be provided in part by specialists from the agrochemical industry, who will need to have a greater involvement in the development of new technology rather than simply marketing chemical products for existing equipment as in the past. The development of electrodynamic droplet production and trajectory control, so that spray application is less dependent on wind conditions, is one of the major steps forward in providing more efficient means of chemical transfer, but market acceptance of such a revolutionary technique will depend on the cost of specialized formulations with their advantage of droplet size control and their novel packaging. The provision of a suitable range of chemical agents is also essential to enable the user to cope with the varied pest complex in any particular agroecosystem. Hand-held spinning disc equipment is already playing a major role, providing chemical control for farmers who would otherwise be unable to apply pesticides owing to lack of water. In the U.S.A. and the U.K., controlled droplet application is beginning to gain greater acceptance. Worldwide further development of aerial spraying will occur where pests need to be controlled over extensive areas, but in the U.K. in the future the emphasis will continue to be on vehicular sprayers. In the future, on larger farms, there may be advanced vehicles with computer controls of flow rate, droplet size, charge:mass ratio and swath width, the appropriate chemical being selected in relation to the input of crop monitoring data. Such sophisticated systems will require a high level of management, not only of the pests by integration of pesticides with other control strategies, but also in crop production to optimize profit instead of aiming at maximum yields.

In this paper on the technology of pesticide application, acknowledgement must be made to the pioneering of spinning disc sprayers particularly for Third World farmers by Mr Edward Bals and more recently to the invention of the 'Electrodyn' by Dr Ron Coffee.

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