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A Review of the Control of Odour Nuisance from Livestock Buildings: Part 1, Influence of the Techniques for Managing Waste Within the Building

D. H. O'Neill; V. R. Phillips*

Silsoe Research Institute, Wrest Park, Silsoe, Bedford, MK45 4HS, UK

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Malodorous emissions from livestock buildings are caused by waste products, particularly manure. The published information on how waste management practices influence odour production and emission has been reviewed, but the shortage of objective odour measurements makes it difficult to give practical recommendations with confidence. Some recommendations for research are, however, proposed.

The main factors in livestock management have been analysed; these are waste removal, waste decomposition, design of the floor of the building, treatments that may be applied to the waste within the building (e.g. changing its pH) and the use of bedding materials. The interactions between most of these factors confound the analysis, but the evidence indicates that the main options for reducing odour production, odour emission or odour nuisance are frequent waste removal from buildings, or the prevention of anaerobic conditions developing in the waste.

Reduction of the moisture content of the waste has been reported to reduce odour production. This may work by inhibiting the development of anaerobic conditions and it may explain why the use of bedding has been found to reduce odour. However, adequate odour measurement data on using different bedding materials and on other waste management practices must be gathered before any firm conclusions can be drawn.

The relevance of information on emissions of ammonia from livestock buildings is briefly considered. Although ammonia concentrations in air do not show a good correlation with odour strength, nevertheless any step taken to reduce the ammonia emissions from a livestock building ought also to reduce the odour emissions and vice versa.

1. Introduction

Odours in livestock buildings are caused by decomposing proteinaceous waste products such as faeces, urine, skin, hair, feed and, where it exists, bedding, all at various stages of decay. The management of waste is concerned mainly with how these materials are moved and stored, and this, in turn, is influenced mainly by the design of the livestock building (of the floor in particular) and by the quantity and nature of bedding material used. In the following sections, the relatively small amount of published information which reports the influence of the technique of waste management on the production or emission of odour is reviewed. Inevitably, different aspects of waste management (such as waste removal procedure and floor design) interact but, as far as possible, the effects of changing one variable at a time are analysed.

* To whom correspondence should be addressed.

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2. Waste removal

The most direct way of assessing the effects of waste removal on odour production is to consider how the composition of waste changes as it ages. In this respect faeces are the most important component of waste, first, because they are biologically active, and second, because, except where a substantial quantity of bedding is used, they make up the majority of the waste material. Furthermore, because faeces are biologically active, the nature of the chemical changes due to ageing depends on the conditions of storage, namely, whether it is aerobic or anaerobic. It is generally accepted[1,2] that slurry (i.e. faeces and other waste without bedding) or manure, which has become anaerobic is more likely to produce objectionable odours than is slurry or manure decomposing aerobically. Phillips and Bulley[3] state that continuous aeration of liquid swine manure is a means of reducing odour production, through avoiding the wide variety of malodorous compounds produced during storage under anaerobic conditions. They also reported, partly in support of this assertion, that aerating anaerobically stored swine manure reduced the odour strength of the head-space gas. ("Odour strength" is the number of dilutions required before a sample of odorous air is perceived as odourless by 50% of the members of an odour panel.) Williams and Evans[4] reported that storing piggery slurry anaerobically increased the offensiveness of the head-space gas. ("Offensiveness" is the degree of unpleasantness ascribed to an odour following an individual subjective assessment.)

However, since it is not practicable to aerate livestock waste in a controlled manner on the floor of a building, the consequences of anaerobic decomposition must be considered. Table 1 shows how, according to Williams,[5] the concentrations of some of the malodorous compounds in piggery slurry increased over a 24-h period of anaerobic storage.

In Table 1, the term "fresh" refers to slurry that had accumulated over 24 h in a collection tray, and so some anaerobic decay may have already occurred even in the "fresh" material. Williams' results[5] show that the concentrations of all these malodorous compounds increased, suggesting that if such conditions should occur on the floor of a livestock building, then the odour in the building atmosphere would increase. Thus, any means of preventing the development of anaerobic conditions in the waste lying on the floor of a building is likely to reduce the odour problem. In particular, prompt removal of the waste from buildings altogether is a certain way of avoiding production of the very offensive odours associated with anaerobic decomposition. It should be emphasized that

Table 1

Change with time of concentrations of malodorous compounds in anaerobic storage of pig slurry (after Williams[5])

	Concentration, mg l⁻¹		
Chemical compound(s)	*Fresh slurry*	*Slurry stored anaerobically for 24 h*	*% increase*
acetic acid	1233	1923	56
propionic acid	310	571	84
i-butyric acid	25	52	110
n-butyric acid	184	263	43
n-valeric acid	49	85	75
methyl-valeric acids	33	81	150
phenol	5·6	13·5	140
p-cresol	24·9	31·4	26
p-ethylphenol	0·7	0·8	12
indole	2·1	5·3	160
skatole	5·0	5·8	17
total sulphides (as S)	1·6	23·6	1350

Table 2

Odour strength in pig and poultry housing air with different waste management systems (after van Geelen and van der Hoek[8])

	Pig housing				*Poultry (layers) housing*			
	Slurry storage		*Dry manure storage*		*Belt manure system*		*Slurry storage*	
	Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
Odour strength (Odour units/m³ air)	97	20–200	39	11–70	59	11–109	238	94–412

the use of anaerobic treatment is different from the uncontrolled decomposition described above, and that anaerobic treatment, normally applied to slurry once it has been removed from the livestock building, can be effective in controlling slurry odours.

Different waste removal and management systems, including those where some accumulation of waste is unavoidable (such as in broiler production) have been found to affect odour production. A comparison made by van Geelen and van der Hoek[8] of waste systems for pig and poultry units included odour strength measurements (Table 2). However, no details were given either of the design of the different waste systems or of how or where the air was sampled to give the reported odour strength measurements.

It could be inferred from the data in Table 2 that storage of slurry within the building should be avoided if it is desirable to minimize odour production. In the case of pig housing, removal of the liquid fraction of the manure appeared to reduce the odour strength and, in the case of the poultry housing, frequent or continuous removal of manure from beneath caged layers appeared to reduce odour strength. However, application of the belt technique to broilers, where the stock are usually kept on the floor, would be rather complicated, and may present insuperable practical problems, especially for young broilers.

It should be noted that the data in Table 2 are odour strengths and not odour emission measurements. In order to determine the odour emission from the buildings, and hence assess how much nuisance the buildings may cause, the ventilation rate through the buildings must be known: the odour emission rate is then the product of the odour strength and the building ventilation rate.

3. Floor design

In buildings where stock are kept on the floor, the design of the floor influences how the waste can be removed, or managed in general. Ideally, livestock production should be considered as a complete system, with all the major components such as the building, its floor, the feeding, waste and husbandry sub-systems, properly matched to one another.

Braun *et al.*[7] report odour measurements taken at selected locations in various pig buildings with different waste removal systems, described, with one exception, by reference to floor design. Their measurements are given in Table 3, and like those in Table 2, are of odour strength. Judging from the standard deviations given in Table 3, there is no significant difference between the reported mean odour strengths for the different removal systems at each location. Without further information on how Braun *et al.*[7] collected their samples or on the building ventilation rates, no further inferences can be drawn. Furthermore, direct comparison with other odour strength measurements, such as those in Table 2, would not necessarily be valid. The results of Braun *et al.*[7] could be

Table 3

Odour strength of air in pig buildings with different waste removal systems (after Braun et al.[7])

Waste removal system	*Odour strength: mean dilutions to threshold (standard deviations)* Outside pen		Lying area		Slurry channel	
Solid manure	165	(76)	179	(106)	375	(—)
Partially slatted floor	162	(98)	190	(110)	458	(119)
Partially slatted floor with recirculation for washing	243	(73)	209	(46)	312	(102)
Fully slatted floor	108	(74)	103	(56)	410	(122)
Fully slatted floor with recirculation for washing	219	(82)	199	(50)	336	(103)

interpreted tentatively to mean that flushing slurry channels (i.e. "recirculation for washing") increases odour strength outside the pens and near the lying areas, but reduces it in the channels themselves. Klarenbeek *et al.*[8] found that frequent slurry removal and flushing the channels with aerated slurry reduced the odour emission from pig finishing buildings. Their results, which include not only odour emission but also the rates of production of two groups of chemicals (acids and aromatics) and of ammonia, for different types of floor in the building, are given in Table 4. In this table, "odour emission" is measured in m^3 diluent air per hour per kg live-weight required to reach the threshold of perception, "total acids" comprise acetic, propionic, *n*-butyric, *i*-butyric and *n*-valeric acids, "total aromatics" comprise phenol, *p*-cresol, indole, skatole, and the type of floor described as "Danish" consisted simply of a lying area with an open slurry channel adjacent to it.

In the discussion of their results, Klarenbeek *et al.*[8] commented that odour emissions for different types of floor were roughly in the same ratios as the manure surface areas for the different types of floor. This led them to suggest, that, according to their observations, a reduction in slurry surface area would result in a reduced building odour emission. Klarenbeek *et al.*[8] compared their 1980/81 results with those of an earlier (1975) Dutch study and found considerable differences. The earlier study was conducted during summer only, but even when Klarenbeek *et al.*[8] considered their summary data separately, their 1980/81 findings were quite different from those obtained in 1975. The details are given in Table 5.

The only explanations offered by Klarenbeek *et al.*[8] for these differences were either differences in the methodology for obtaining the sensory information, or variations in odour emission from year to year. Klarenbeek *et al.*[8] acknowledged that their units of odour emission per kg live-weight might be questionable, especially when comparing different pigs in different buildings at different times, but they defend their choice by the absence of better or more meaningful units. They ascribe the lower odour emission during

Table 4

Emission rates of odour and of particular chemical compounds from pig buildings, according to type of floor (averaged over whole year) (after Klarenbeek et al.[8])

Floor types	*Number of pig places*	*Odour emission*	*Total acids* ($mg\,h^{-1}$)	*Total aromatics* ($mg\,h^{-1}$)	*Ammonia* ($g\,h^{-1}$)
Danish	180	20	1304	53	8
Half-slatted	105	76	1675	48	26
Half-slatted	200	90	7287	227	76
Fully slatted	400	156	8315	382	212

Table 5

Odour emission from pig finishing buildings according to floor type: summer period only (after Klarenbeek et al.[8])

Floor type	*Building odour emission* ($m^3 h^{-1}$ (kg live-weight)$^{-1}$) 1975 study	1981 study (summer data)
Danish (open channel)	79	35
Half-slatted floor	95	147
Fully-slatted floor	109	225

the winter period compared to that during the summer period (this is evident from comparing Tables 4 and 5) mainly to lower slurry temperatures and lower building ventilation rates in the winter.

Van Ouwerkerk and Voermans[9] compared the performance of two concrete-floored broiler houses which were identical except that the floor of one of them was given 50 mm of polystyrene insulation, topped by plastic film. The immediate aim was to reduce condensation in the litter, and the % dry matter of the litter was indeed increased. Up to the 30th day of the broiler crop, odour emission rate was also lower from the house with insulation, but after the 30th day the two houses had similar odour emission rates.

4. Waste treatment

The way in which waste is treated or handled, especially if it is not promptly removed from a livestock building, but stored in it, has been shown to affect odour production in, or emission from, the building.

Barth and Melvin[10] commented that elimination of odour around animal production units is neither technically nor economically feasible, but that there are a number of management options available to minimize odour production, emission and complaints. Although Barth and Melvin[10] did not give any practical details of these options, they did suggest some waste management treatments. These suggestions were based on the assumption that undesirable odours result from anaerobic bacterial activity and hence that any means of suppressing anaerobic decomposition (e.g. reducing moisture content or temperature, varying pH of the slurry or applying bacteriocides) would control odour. These treatments are very likely to change the nature of the odour, possibly making it less offensive, but their effect on odour emission or odour strength has not been defined.

Tjernshaugen[11] monitored the concentrations of ammonia and hydrogen sulphide in the air in 81 pig buildings. He concluded that high ammonia concentrations were associated with infrequent cleaning and with a high percentage of solids in the slurry, and that hydrogen sulphide concentrations increased dramatically when the slurry was agitated. Raabe *et al.*[12] investigated the benefits of flushing poultry manure from under caged layers instead of scraping it or allowing it to accumulate in a collection pit. One of the several benefits they attributed to a hydraulic manure-flushing system was reduced odour intensity. Their so-called odour intensity, which is presumably odour strength, was stated not to exceed 31 dilutions to threshold in the house with the flush system, although it ranged from 31 to 170 dilutions to threshold in the other houses. Raabe *et al.*[12] stated that at two other farms the odour intensities were even lower, possibly because these used natural ventilation. The maximum odour level they reported for any sample was 170 dilutions to threshold. Unfortunately, these results are of little practical value without a knowledge of the building ventilation rates. These would allow the building odour emission to be calculated and comparisons made with other waste handling techniques.

Sobel[13] evaluated a number of waste handling and management options for poultry manure, in terms of odour offensiveness. Dried manure was found to be generally less offensive than manure which had been diluted with water, and, of four different removal techniques, frequent mechanical scraping was found to cause the lowest level of odour offensiveness in the ventilating air of the poultry house studied. The results indicated that, to minimize odour offensiveness, manure should be removed rather than be allowed to accumulate. One of the techniques studied by Sobel,[13] and found to be less offensive than accumulation, was a combination of part-drying and part-removal; a mesh screen, supported above the pit, held some of the solid fraction of the manure falling towards the pit; this residue dried relatively quickly and was scraped off the mesh screen daily. Kroodsma[14] described a similar system in which filter nets were fitted under the floor slats in a piggery. The liquid fraction of the slurry flowed into the channels in the usual way, but the solids were retained on the nets, which could be cleaned daily. Kroodsma[15] later reported odour measurements on his net system operating in a piggery: odour emission per pig was halved and the annual costs of such a system were not excessive.

Klarenbeek *et al.*,[8] quoting two studies preceding theirs, reported that "frequent removal of slurry by washing it down with aerated manure causes a significant reduction in odour emission". The investigation by Klarenbeek *et al.*[8] themselves included a limited number of odour measurements from a finishing pig building (280 pig places) with a fully slatted floor and slurry washed down with aerated manure. The odour emission they reported was 85 $m^3 h^{-1}$ diluent air per kg live-weight, which was considerably less than the value given in Table 4 of 156 $m^3 h^{-1}$ per kg live-weight for without washing down. For the summer period only, the odour emission with washing down was 159 $m^3 h^{-1}$ per kg live-weight, also lower than the corresponding figure in Table 5 of 225 $m^3 h^{-1}$ per kg live-weight without washing down, but not less than 109 $m^3 h^{-1}$ per kg live-weight, the result obtained in the 1975 study referred to by Klarenbeek *et al.*[8]

Phillips *et al.*[16] discussed the effects of changing slurry pH on the odour given off from it. The pH of the slurry determines the degree of ionization of its constituents and hence the vapour pressure of the constituents and their collective odour. Compounds that are ionized in solution are unable to exert a vapour pressure. Applying this principle to slurry, Phillips *et al.*[16] stated that hydrogen sulphide will have a considerable vapour pressure and odour when the pH is near 7 but not otherwise. Phenolic compounds exert a maximum vapour pressure, and consequently odour, at the normal pH of fresh slurry (around 7) and so contribute to its characteristic odour. As the pH is raised further, the acids present dissociate and the odours of the amines and ammonia become prominent. Dorling[17] reported odour measurements from some poultry houses which, he suggested, indicated that the odour emission from poultry houses with open pits is independent of the age or quantity of manure in the pit. He attributed this to the repeated formation of a dry skin over the surface of the accumulated manure. He added that wet, anaerobic conditions would exist beneath this skin and that highly odorous gases would be released when the manure was disturbed and exposed to the air during cleaning of the pit (cf. Tjernshaugen[11]). While it is feasible that a dry skin may form on poultry manure, this is unlikely to be the case with piggery slurry, which is very much wetter. For pig buildings, therefore, odour emission may not be independent of the age or quantity of manure in the pit. Dorling's results[17] suggested that a slatted pit causes less building odour emission than does an open pit and so they agree with the findings of Klarenbeek *et al.*[8]

Dorling[17] also comments on the complicated interaction between building odour emission and building ventilation rate. As the ventilation rate increases, a greater amount of odorous, volatile compounds is likely to be released from the waste (as it dries) but the

increased number of odorous molecules could be less concentrated as a result of the greater air flow, and therefore could create less of a nuisance. According to Dorling,[17] odour emissions of up to even 1 260 000 $m^3 h^{-1}$ would be unlikely to cause a nuisance. These emissions were from battery poultry houses containing 6000 birds. However, a smaller house of 1000 battery hens, also with an open pit, could, Dorling[17] suggested, cause a nuisance since it produced an odour emission of nearly 2 900 000 $m^3 h^{-1}$. These values can be compared with the results of Klarenbeek *et al.*,[8] for example, given in Table 4. If the building with the "half-slatted" floor were full of 90 kg pigs, then the odour emission rate from the building would have been 2 268 000 $m^3 h^{-1}$. It is generally believed (e.g. Robertson[18]) that dirty animals, especially pigs, on which there is a substantial coating of dried faeces, are more odorous than cleaner animals. The frequent removal of waste from the lying area should keep the animal cleaner and thus reduce odour. However, Klarenbeek *et al.*[8] reported that, contrary to their expectations, fouling of the lying area seemed to have no significant influence on the odour emission from pig buildings.

5. Use of bedding

The amount of bedding, together with the waste removal system, determines the extent and nature of the waste decomposition on the floor of a livestock building. The two properties of bedding likely to exert the greatest influence on odour production are its absorptivity and its physical structure. Most bedding materials such as straw, wood-shavings and shredded paper are highly absorbent and therefore tend to dry the waste. In the previous section, the drying of poultry manure was reported to be a means of reducing odour offensiveness[13] and so the use of bedding may assist odour abatement in general. Nielsen[19] believes that "(odour) problems arise from broiler units due to the manure produced during the last 2 weeks of the crop being more than the bedding material can absorb". According to van Geelen and van der Hoek,[8] dry pig manure was less odorous than slurry (Table 2) but the method of drying, e.g. by air movement or absorption into bedding material, was not reported.

When straw is used as bedding, farmyard manure (FYM) is produced. FYM has been reported as having a more acceptable smell than slurry.[4] This may be due to the physical structure of straw encouraging composting (i.e. thermophilic aerobic decomposition), thereby inhibiting anaerobic decomposition and thus the production of more malodorous compounds. If, however, FYM is stored in a manner that prevents composting, e.g. if it is stored in a large compacted heap, there will be high odorous emissions when the heap is disturbed. The proper management of middens demands considerable effort, particularly when compared to that for an automated slurry storage system.

The use of bedding, especially straw, as a means of abating odour does not yet seem to have been investigated scientifically; the evidence to date is only anecdotal. The need for such information is increasing, both because the welfare recommendations for pigs[20] encourage the use of bedding and because other abatement techniques are costly (see e.g. O'Neill *et al.*[21]). There is little published information on the use of different materials for livestock bedding and only one reference has been found on the odour abatement potential of bedding material. This is in the report by Klarenbeek *et al.*[8] who conclude from a study by Missfeld[22] that "the use of litter to produce solid manure also causes a reduction in odour emission".

Laboratory tests have been made to evaluate Russian peat and a number of straw preparations,[23] or paper,[24] as alternatives to wood-shavings for poultry litter. Parsons *et al.*[25] assessed the use of chopped straw and mushroom compost as broiler litter. However, all these evaluations were in terms of the productivity and health of the poultry, and no mention was made of any change in odour production. It would be useful to investigate bedding materials other than straw, for pigs and cattle particularly, to assess whether some of the waste handling problems associated with straw could thus be reduced or avoided.

Armstrong[28] compared the costs of slurry and of straw-based waste systems, when examining the implications of implementing the welfare code for pigs.[29] Housing pigs in stalls was cheaper than housing in a yard with a straw-based waste system. The difference seemed to arise mainly because yard housing was inherently more expensive, rather than because of the different waste management systems, although the actual costs of the latter alone were not given. Despite this, Armstrong's report[28] is useful for its summary of the waste-handling problems of straw-based systems, and it also emphasizes the pig welfare benefits of using bedding.

The costs of a straw and of a slurry system have been compared[27] for two similar 250 sow units with pigs taken to bacon weight (c. 90 kg). The straw unit was found to be 5% cheaper to erect than was the slurry unit, but the annual running costs for the straw unit were 59% more. With depreciation, labour and other overheads accounted for, the total annual cost of the straw unit was calculated to be 12% less. Although this saving was considered insignificant compared to the annual turnover, it was demonstrated that the currently recommended animal welfare practice does not necessarily cost the farmer more. FYM systems create more engineering problems, particularly in the removal of old material from pig buildings and in the movement and distribution of fresh bedding. Hence, even though they are not necessarily cheaper, and may also result in the emission of more odour, slurry systems may still be preferred by farmers on grounds of reliability.

6. Ammonia emissions from livestock buildings

During the time that this review was being compiled, concern over emissions of ammonia from livestock buildings has risen sharply, as evidence gathers that such emissions contribute significantly to the problems of forest dieback.[28-30]

Ammonia is, of course, one of the (many) compounds in the air leaving livestock buildings, the combined overall actions of which produce the characteristic odour. However, efforts to use ammonia as a simple chemical indicator of odour have so far met with only limited success.[28]

Recent studies specifically on ammonia emissions have not been included in this review. Nevertheless, because of physicochemical similarities, we except that any change to a livestock building, made with the aim of reducing ammonia emissions from it, is likely also simultaneously to reduce odour emissions.

7. Conclusions

In general, the rather limited evidence presently available indicates that the odour from a livestock building does increase as waste accumulates in the building or in channels or pits beneath it. The only waste management technique which can, without question, reduce livestock building odour emission is removal of waste from the building. It is not clear whether the increase in odour as waste accumulates is caused predominantly by the extra volume of waste or by the biological changes taking place within it as it ages and anaerobic conditions develop. If frequent removal of waste is not practised, there is some evidence to suggest that inhibiting the development of anaerobic conditions by moisture reduction or by flushing slurry channels in livestock buildings with aerated slurry can reduce the building odour emission.

For waste within the building, avoidance of uncontrolled anaerobic degradation is the cornerstone of the odour-reducing techniques reported in the literature. Although this may make waste less offensive, it does not necessarily reduce its odour strength. Reduction of the moisture content of the waste in a building has been found to inhibit odour production. The obvious methods here are air drying or the use of bedding, but both have their drawbacks. For example, drying, especially if heat is used, may increase odour production by driving off more volatiles, whilst the use of bedding increases the mechanical problems of waste handling. Different bedding materials should be evaluated for their odour abatement properties, particularly as bedding is recommended for welfare reasons. Furthermore, waste management systems designed to handle bedding are not necessarily more costly than slurry systems.

The manner in which waste is removed from a building depends heavily on the floor design and therefore on many other aspects of livestock production. When planning a livestock enterprise it is essential to consider all the interacting factors together, in order that a properly integrated system can be designed.

In the few publications which have dealt with livestock building odour, the assessments obtained from sensory tests have not been reported in a consistent fashion, nor have sufficient details been given to enable comparison between different authors' results. Four papers[6-8,12] have been found which report quantified odour measurements: that of Klarenbeek *et al.*[7] using the concept of odour emission and the three others using the concept of odour strength or of number of dilutions to threshold. Raabe *et al.*[12] however, described their measurement as odour intensity, which is something different. The dilutions to threshold measurements reported in these papers range from 31 to 458 but, without knowing the circumstances, these numbers are of little use.

In summary, the most certain way of avoiding odour nuisance from a livestock building is the frequent removal of waste. There is also reasonably strong evidence that odour emission can be reduced if anaerobic degradation can be prevented or at least suppressed. Further research is recommended into possible methods of achieving this through the control of moisture content, temperature or pH, with or without straw or other bedding, and including careful sensory assessments.

Engineering research into better methods of frequent (e.g. daily) waste removal within the context of the livestock management system is advocated.

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A Partitioned Energy Transfer Model for Spray Impaction on Plants

R. D. Brazee;* D. L. Reichard;* M. J. Bukovac;† R. D. Fox*

* Application Technology Research Unit, Agricultural Research Service, U.S. Department of Agriculture, Ohio Agricultural Research and Development Center, Wooster, Ohio, U.S.A.

† Department of Horticulture, Michigan State University, East Lansing, Michigan U.S.A.

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Of the processes active in foliar spray application of pesticidal and biologically active compounds in agriculture, impaction and deposit formation have been relatively neglected topics of investigation. Experimental research on spray-dynamic phenomena at the plant interface shows that rebound of droplets from some plant surfaces is a significant factor limiting effective application and retention. An energy transfer model was developed which predicts probable reflected velocity factors, or coefficients of restitution, for the first-impact rebound of droplets from a plant surface. The model, based on the principle of equipartition of energy as a limiting case, requires uniform distribution of incoming kinetic energy, on the average, among the dimensions of energy transfer modes involved. Energy transfer modes identified include droplet and plant-surface elastic deformation, impulse or shock, and plant-surface alteration. Available energy from elastic deformations is partitioned among droplet translation, rotation, oscillatory and internal energies when rebound occurs. The model will help determine the most effective ways to modify energy transfer in order to limit droplet rebound and improve spray retention.

1. Introduction

Foliar spray applications of biologically active compounds in crop production consist of the complex interacting processes of atomization, transport, impaction, retention, deposit formation, movement on or into the plant and finally physiological effect. Of these processes, impaction, retention, and deposit formation at the plant surface have been relatively neglected areas of spray research. With increasing costs, greater numbers of highly active chemical or biological control agents, and the need to limit environmental pollution, more attention must be given to all phases of spray application, particularly to mechanisms at the plant interface, to achieve more efficient and consistent spray performance. This demands a more detailed understanding of relationships among physiochemical characteristics of spray solutions and the surface microstructure and chemistry of plants.

Some research on spray droplet retention on various surfaces has been done. Araki and Moriyama[1] conducted theoretical and experimental studies of impaction of water droplets on hot metal surfaces, a concern for spray cooling applications, such as in steel rolling mills. High-speed drum photography was used in experimental observations, with particular attention to deformation and disintegration of droplets. Droplet film flow and breakup were found to be related to vapourization effects and to Weber number, defined as $We = \rho U^2 r/\sigma$, where ρ is liquid mass density, U is droplet velocity normal to the surface, r is droplet radius and σ is the surface tension coefficient.

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