Health Significance of Airborne Microorganisms from Wastewater Treatment Processes Part II: Health Significance and Alternatives for Action

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Health significance of airborne microorganisms from wastewater treatment processes

Part II: Health significance and alternatives for action

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Part I of this review summarized the results of field studies and other pertinent investigations on the emission and spread of airborne microorganisms from wastewater treatment processes. Part II addresses the interpretation of these results. It examines the several factors influencing the generation, characteristics, and measurement of viable wastewater aerosols and their dispersion and survival in air. This examination emphasizes the relative importance of these factors in monitoring viable wastewater aerosols and in controlling them should this be found necessary.

Part II also evaluates existing data on viable wastewater aerosols in terms of health significance to treatment plant workers and other persons exposed to the aerosols. Part II concludes with a discussion of alternatives for future actions related to the subject. Table I contains an index to the reference lists of both Part I and Part II.

For convenience, some terms related to aerosol characteristics are defined as follows: A viable particle is an airborne particle containing living matter as demonstrated by growth or replication under defined conditions. In this review, a viable particle is one containing at least one bacterial cell capable of forming a colony under conditions selected by the investigator. The viable aerosol is the mass or cloud of viable particles emanating from a source. The diameter of a viable particle refers to its aerodynamic (equivalent) particle diameter, which is the diameter of a unit-density sphere that behaves in the same way as the particle with respect to an aerodynamic characteristic, usually, settling velocity.[55] This value is often used because it more accurately reflects the behavior of an airborne particle and is usually more easily measured than is its physical diameter. The diameter of an aerosol as a whole refers to the geometric mean of the diameters of its individual particles.

Evaluation of Significant Factors Affecting the Emission and Spread of Viable Aerosols from Wastewater

Sources. The published reports of field studies of wastewater as a source of viable aerosols are summarized in Table II according to the collection, treatment, and disposal processes examined.

Not illogically, the processes most closely scrutinized have been those that mechanically assist the aerosolization of wastewater. In these studies, regardless of the sampling methods used, significantly higher numbers of airborne bacteria were reported recovered from downwind samples than from upwind or other control samples, with only one exception.[3] In most of the studies, only aerated processes were examined. Those investigators[4, 7] who did make direct comparisons between viable aerosols from aerated and more quiescent processes generally did so as a preliminary screening to identify the primary aerosol sources. They invariably re-

TABLE I.—Index to Reference Lists

Type of Reference	Reference Number
Direct field investigations of viable bacterial aerosols from wastewater	
Primary studies cited in this report	1–16
Studies cited from abstract or brief summary	17–25
Related field and laboratory investigations	
Laboratory studies on generation of viable bacterial aerosols from wastewater	26–27
Field studies on protein-bearing aerosols from wastewater	28–31
Reviews and investigations of the health significance of viable aerosols from wastewater	32–41
Other literature cited	42–54 (Part I) 42–74 (Part II)

ported recovering much larger numbers of airborne bacteria downwind from the aerated sources than from the nonaerated sources; they subsequently concentrated on the aerated sources, concluding explicitly or implicitly that the nonaerated processes were minor contributors to the airborne bacterial load. That some bacteria are emitted to the air from nonaerated wastewater is evident, [1, 9, 10] but the data [4, 7] indicate a minor contribution from such sources.

If the premise that aeration processes are the major contributors to the viable aerosol load from wastewater is accepted and the need for further investigation into possible associated health hazards is realized, it follows that future studies should include aerated wastewater sources that have not been examined adequately, if at all. These include aerated lagoons, aerated sludge digesters, forced-draft trickling filters, some of the newer paddle and turbine rotor aerators,[56] and land application by spraying and sprinkling. The handling and processing of dried sludge may represent another significant viable aerosol source.[40]

Which aerated wastewater source emits the most airborne bacteria does not seem to be important. Direct comparisons of processes [8, 10, 11] indicated that extended aeration plants emitted 27 percent as many airborne bacteria per unit surface area as activated sludge aeration tanks and that somewhat greater numbers of airborne bacteria were recovered near a preaeration tank than near an activated sludge aeration tank or a trickling filter. Apparently, most aerated wastewater processes may be comparable as sources of airborne bacteria.

An exception to this generalization may be the land application of wastewater by sprinkling and spraying. Because these methods may project all of the wastewater into the air as droplets, as much as 1 percent of the liquid is aerosolized,[37] as opposed to probably a much smaller fraction with other aeration methods. Thus, there is at least a theoretical possibility of producing a very concentrated viable aerosol load. This feature, plus the nondefinitive results of field studies on the subject,[3, 18–21, 25] makes the evaluation of the health implications of viable aerosols from the land ap-

TABLE II.—Investigations Related to Viable Aerosols from Various Processes

Type of Process Examined	Reference Number	
	Direct Field Studies	Related References
Flow in sewer	1,24	
Grit/grease chamber	9	
Flow in channel	4,10,11	
Preaeration tank	7,8	
Primary sedimentation tank	3,4,7	
Activated sludge aeration tank*	2,3,5–11, 13,14,15,23	28–31,56
Trickling filter	2,4,7,8,12,16	
Extended aeration plant	10,11	
Final sedimentation tank	7	
Sludge digester	4	
Sludge drying bed	4	
Land application by spray or sprinkler	3,18–21,25	35–39, 69,73,74
Simulated aerated wastewater		26,27
Other or unspecified processes	22	24,51,52, 72

* In references 3 and 15, the type of aeration tank is unspecified, but the description fits an activated sludge aeration tank.

plication of wastewater a high-priority area for future studies of airborne organisms from wastewater processes.

Thus, aerated wastewater sources that have been examined yielded downwind recoveries of viable bacterial aerosols of about the same order of magnitude. Several potentially significant sources have not been examined adequately. Land application of wastewater by spraying or sprinkling may have a particularly high potential for producing viable aerosols.

Microorganisms assayed. The types of viable microorganisms recovered from air downwind from, and attributed to, wastewater treatment processes are summarized in Table III. Viable aerosols were in every case identified according to their bacterial content. No viral assays were made. Other investigators [28-31] have assayed protein-bearing particulates in air at wastewater aeration tanks without determining viability.

For the most part, investigators measured the natural bacterial aerosol from aerated wastewater, either by total viable particle recovery, by total recovery of an index organism, or by both methods. Coliform organisms were generally used as the index organism.

Studies using the tracer organisms *Bacillus subtilis* var. *globigii* [8] or *Serratia marcescens*,[13, 14] added to the wastewater at the plant or in sewers upstream, demonstrated the aerosolization of viable bacteria from aeration tanks but did not measure downwind transmission. Some investigators [13-16] also assayed the bacterial popula-

TABLE III.—Microorganisms Assayed and Identified in Field Studies of Viable Bacterial Aerosols from Wastewater

Microorganisms Assayed	Reference Number												
	1	2	3	4	5	7	8	9	10,11	12	13,14	15	16
Type of Assay													
Total count		x		x	x		x	x	x	x	x	x	x
Index organism count		x	x	x	x	x	x	x	x	x	x		x
Identification													
Escherichia coli		x		x				x	x		x		x
Aerobacter sp.				x				x	x		x		
Coliforms	x	x	x	x	x	x	x	x	x	x			x
Klebsiella								x	x		x	x	
Providence								x					
Shigella								x					
Salmonella								x	x			x	
Bacillus typhosus	x												
Staphylococcus aureus											x		
Streptococci									x				
Hemolytic strep.												x	
Mycobacterium												x	
Acid-fast bacilli												x	
Enterobacteriaceae									x				
Proteus								x	x		x		
Serratia marcescens											x		
Pseudomonas								x			x		
Bacillus subtilis var. *globigii*							x						
Other	x							x	x		x	x	x
Organism source													
Natural aerosol	x	x	x	x	x	x	x	x	x	x	x	x	x
Seeded tracer	x	x					x				x		
Index Organism Suggested			a					b	c		d		e

Note: a = Coliform, b = *Klebsiella*, c = Total bacteria count, d = *Alcaligenes faecalis*, and e = *Escherichia coli*.

tion of the wastewater being aerated as an adjunct to their aerosol assays.

In addition to measurements of bacterial concentrations in air, a large variety of individual genera and species were identified from recovered particles. These included several pathogenic genera and species, and some investigators seemed to equate the presence of these bacteria with virulence. Only once, however, was the virulence of recovered bacteria demonstrated directly, and this was with animal inoculation studies.[15] Indirect evaluations of virulence included demonstration of beta-hemolysis by recovered organisms[8] and retention of encapsulation capacity by *Klebsiella*.[9]

On the basis of field recoveries, several bacteria were suggested as possible indexes for evaluating bacterial aerosols from wastewater. These were coliforms,[3] *Klebsiella*,[9] total bacterial count,[10] *Alcaligenes faecalis*,[13, 14] and *Escherichia coli*.[16] The matter, however, seems more complex than the mere designation of a particular organism. A much lower survival rate in air has been observed[2, 9, 10, 11, 17] for intestinal bacteria than for bacteria occurring normally in air. The species-selective aerosolization of bacteria from the surface of liquids has been demonstrated.[26] Thus, an index organism selected by virtue of its being representative of the liquid wastewater population may not be representative of a wastewater aerosol in terms of either bacterial emission or survival. Such an organism might be even less representative of the virus population of an aerosol.

Using the total bacterial count in air as an index for evaluating aerosols has been proposed.[10, 26] This would eliminate the need for preselection of an index organism but might not be representative of the pathogenicity of the aerosol, particularly as related to viruses. In addition, using total counts would increase the possibility of an undetected interference from sources other than the wastewater. *Streptococcus viridans* has been suggested[17] as an index organism for air contamination in general; some streptococci have been recovered from air near wastewater aeration tanks.[10, 15]

In sum, a variety of bacterial genera and species, some of which are pathogenic, has been recovered from air downwind from aerated wastewater. Information on the virulence of bacterial aerosols generated from wastewater is sparse; information on viral aerosols is nonexistent. There is a need to develop a valid index for assaying such aerosols.

Sampling methods. A variety of air sampling methods was used in the field studies. The features and limitations of these methods have been reviewed[45, 57] and are summarized briefly in the following paragraphs.

Agar settling plates primarily measure settleable viable particles (a viable particle is one containing at least one viable cell) per unit of agar surface area and unit exposure time. Agar plates with the agar surface facing the wind also measure settleable viable particles and, depending on several factors,[58] may measure some viable particles impacted onto the agar surface. Glycerin-coated swabs[15] collect viable particles by the same mechanisms. Microorganism counts recovered by these methods are not directly related to the concentration of viable particles per unit volume of air.

Solid media impactors, such as the Wells centrifuge and the Andersen drum and six-stage impactor samplers, measure viable particles per unit volume of air sampled to the limits of their efficiencies. In addition, the drum sampler can distinguish variations in viable particle concentration with time, and the staged impactor can distinguish the particle size spectra of the viable aerosol. Generally, each viable particle recovered by the solid media samplers results in a single colony when incubation occurs, even though a particle may contain more than one viable cell.

Liquid impingers measure viable particles per unit volume of air; however, collected particles may break up to some extent in the liquid media during sampling, and the colonies counted after incubation will, to that extent, be greater than the number of viable particles in the original aerosol.

The results of field assays of viable wastewater aerosols followed a similar pattern regardless of the sampling methods used; proportionately higher concentrations were recovered near the sources, and much lower concentrations were recovered as downwind sampling distances increased.

Most investigators reported recovered organisms as viable particles or colonies; some reported their counts as "organisms," a term that presumes a single viable cell per particle.

Once a sampling method was selected, it was considered in most of the studies to be 100 percent efficient. Attention was given in some cases to sampler collection losses and the limitations of differential media.[10, 15] However, the possibility of decreased sampler collection efficiency as a result of the aerosol's smaller particle size did not receive major consideration as an explanation of decreased viable particle recovery downwind. Other possible explanations, such as the effects of radiation and relative humidity, predominated.

To evaluate adequately the health implications of viable microbial aerosols from wastewater, a sampling method should have the following features: a reasonably high efficiency in the particle size range of interest (1 to 10 μ diam), the capacity to measure concentrations of viable particles per unit volume of air, the ability to preserve organisms to permit specific identification, and the ability to minimize logistics problems of sampling. In addition, because of the well-established influence of particle size on the degree of retention and site of deposition of inhaled particles, the sampling method should distinguish the particle size spectra of the viable aerosol.

In the field studies reviewed, the Andersen six-stage impactor, a sampler that has all of the features mentioned above, was the preferred sampler, as is evidenced by the fact that it was used in eight of the 13 studies. It has been shown that this sampler can be used for detection and particle size assays of viable viral aerosols in air[59] and that application of a monolayer of oxyethylene docosanol on the agar collection surfaces for moisture retention can overcome some of the disadvantages of this type of sampler caused by the drying of the agar surfaces.[60]

All sampling procedures used in this review showed a similar viable aerosol assay pattern. Samplers capable of providing viable particle size data and volumetric concentrations were preferred.

Microorganism recovery concentrations. Because of the many variables involved, quantitative results among the various investigations reviewed may be compared only in general terms and to show the similarity of trends.

The sampling pattern generally followed was the collection of air samples at or near the downwind side of the aerated wastewater process. Some investigators also collected samples at specified downwind distances; most collected samples upwind as controls. The results were reported in terms of viable particles recovered per unit volume of air or number of colonies recovered on settling plates per unit time of exposure. In this discussion, concentrations have been converted to viable particles per cubic foot and downwind distances to feet where necessary for comparison purposes.

Recoveries immediately downwind from the sources ranged from 9 to 870 viable particles/cu ft (320 to 30,700/cu m) of air on solid media and up to 1,170/cu ft (41,200/cu m) in a liquid media sampler.[9, 13] Recoveries on the plant premises up to 300 ft (91.4 m) downwind from the sources ranged from 0 to 31 viable particles/cu ft (1,100/cu m) of air.[4, 7, 12, 13, 16] Dispersion model calculations[10] predicted a maximum concentration of 10 viable particles/cu ft (350/cu m) of air at 200 ft (61 m) downwind from the aerated wastewater and 3 viable particles/cu ft (106/cu m) at 150 ft (45.7 m) downwind under average weather conditions.

In samples collected beyond the plant boundaries, maximum recoveries attributed to plant sources were 1.3 viable particles/ cu ft (48/cu m) at 1,180 ft (360 m) downwind[15]; 15 (529/cu m) at 2,300 ft (700 m)[16]; and five, three, and 0.1 coliform particles/cu ft (129, 108, and 3/ cu m) at 900, 2,640, and 4,230 ft (275, 800, and 1,290 m), respectively.[12] In a single sample taken 9,900 ft (3 km) downwind from the source, zero recovery above the control concentration was reported.[16]

Upwind control sample recoveries were as high as 86 viable particles/cu ft (3,040/cu m) of air[8] but were generally less than six/cu ft (212/cu m), which compares well with ambient airborne bacteria levels of 1 to 5 viable particles/cu ft (35 to 175/cu m) reported by others.[45]

The recovery patterns were similar within each study; there were relatively high counts per unit volume near the sources and much lower counts as downwind sampling distance increased. Downwind viable aerosol concentrations generally diminished to upwind concentrations within a few hundred feet of the source.

The significance of low recoveries at great downwind distances should be interpreted with care. One investigator[10] concluded that the effect of the wastewater on the viable bacterial aerosol did not extend beyond 150 ft (45.7 m) downwind because the viable aerosol concentration at that point had returned to the ambient concentration. This conclusion may not adequately consider changes in the aerosol's character, as is evidenced by reported recoveries[13–15] of pathogenic bacterial genera from air samples taken downwind from aerated wastewater but not from those taken upwind.

Low recoveries at great downwind distances may be attributed to normal sampling variations. In the reported case of coliforms recovered 0.8 miles (1.29 km) downwind from a trickling filter,[12] for the sampling conditions given, the probability that downwind recoveries in excess of upwind recoveries were the result of sampling variation is not excluded at the 0.09 probability level.[61] Recoveries downwind may also come from sources other than the source being investigated. Such interference has been reported,[9, 10] and the opportunity would likely increase at greater downwind distances.

Because of the above considerations, current data attributing airborne bacteria to wastewater sources more than about 2,000 ft (600 m) away should be viewed with reservation. On the other hand, the persistence of low concentration viable bacterial aerosols from wastewater seems to be established by the literature to a distance of 1,000 ft (300 m) or more.[12, 15, 16]

There is little quantitative information on the spread of viable aerosols downwind from land application of wastewater by spraying and sprinkling. European studies[18–20, 25] have reported coliform or total bacterial counts recovered on settling plates. These cannot be directly correlated to airborne bacterial concentrations. Studies with volumetric air samplers[3, 21] have not been extensive enough to establish a definitive trend.

Therefore aeration processes generate a considerable viable bacterial aerosol, which, in spite of rapid reductions in concentration, persists for at least several hundred yards downwind and perhaps farther. Reduction of the viable aerosol concentration to ambient level may not safely be equated to a lack of further effect because of changes in the bacterial make-up of the aerosol as it passes over aerated wastewater. Interference from other sources has not been adequately controlled in sampling at great downwind distances.

Quantitative information is lacking on the downwind concentration of viable aerosols from the land application of wastewater.

Particle sizes of viable aerosols. Particle sizes of the viable aerosols generated from aerated wastewater were calculated from data presented in several studies[9, 10, 15, 16] that utilized the Andersen six-stage impactor. Except in the case in which the investigator provided a sampler calibration,[10] published calibrations[62, 63] were used to estimate the aerodynamic equivalent geometric mean aerosol diameters (see definitions at the beginning of Part II) and standard deviations. These calculations have been summarized in Table IV along with other reported particle size data on viable and protein-bearing aerosols associated with aerated wastewater.

A few points are worthy of comment. The viable aerosols are clearly in the human respirable particle size range.[17, 64] The geometric mean particle size of the viable aerosol seemed to diminish initially after generation but did not change appreciably afterward.[9, 10, 16] The geometric mean particle size of the downwind viable aerosol may be smaller than that of the upwind aerosol.[10] Protein-bearing aerosols (which might be considered as viable aerosol analogs or as allergy-producing air pollutants) are also in the human respirable size range and are considerably larger than non-protein-bearing particulate aerosols.[28–30]

The geometric mean aerosol diameter range in Table IV of 4.2 to 4.5 μ [16] represents total and coliform bacterial aerosols recovered under both daytime and nighttime sampling conditions at various downwind distances. These variables did not seem to have a large effect on the particle sizes of the viable aerosols.

Studies with simulated wastewater [26, 27] showed recoveries of viable aerosols in size ranges similar to those found in the field studies.

Factors affecting emission of viable aerosols. Aeration is apparently the major factor influencing the emission of viable aerosols from wastewater, as has been pre-

TABLE IV.—Particle Sizes of Aerosols Associated with Aerated Wastewater Processes

Wastewater Process	Type of Aerosol	Distance Downwind from Source (ft)	Geometric Mean Diameter of Aerosol* (μ)	Geometric Standard Deviation	Reference Number
Activated sludge aeration tank	Viable bacteria	0	7.0	2.0	9†
		3–100	4.3–5.1	1.8–2.6	9†
		50	5.8	1.9	10†
		100–140	6.2	1.9	10†
		Upwind	7.8	3.2	10†
		Inside enclosed tank	5–10		15
		Air discharge stack of enclosed tank	3.2	1.9	15†
	Protein-bearing particles	0	40% < 10 (Mean = 11.8)		31
		0–200	2.6	2.4	28
		Upwind	4.1	1.9	28
	Protein- and non-protein-bearing particles	0–200	0.25–0.33	2.5–2.7	28
		Upwind	0.16–0.28	2.3–3.1	28
Trickling filter	Viable bacteria	Various	4.2–4.5	2.0	16†
Simulated aerated wastewater (mg/l of solids)	Viable bacteria				
0		0	3.7–5.7		27
40		0	2.8–3.1		26
130–260		0	4.8–5.8		26
400–1,600		0	2.4–8.6 (Mean = 5.0)		27

* Particle sizes of viable bacterial aerosols are aerodynamic equivalent geometric mean particle diameters. Values from References 26 to 28 are median diameters.

† Values given were calculated from reported data.

Note: Ft × 0.3048 = m.

viously discussed. Other factors have been observed to affect both the emission rate and the character of the viable aerosol.

In laboratory studies with simulated wastewater,[27] an aeration bubble with a 0.5-mm diam produced 3×10^6 viable particles/l of aeration air, while a bubble with a 5.7-mm diam produced only 5,000. Because smaller bubble size promotes oxygen transfer, the use of large bubbles for aerosol control, should it be needed, would conflict with the primary purpose of aeration. This same study showed that the viable aerosol emission rate increased directly with the microorganism concentration in the wastewater up to a concentration of 10^6 to 10^7/ml, at which point all aerosol particles contained at least 1 viable cell. Viable particle emission rates were also found to increase with the total solids concentration in the aerated liquid.

In other laboratory studies, species-selective aerosolization of bacteria[26, 51] and bacterial concentrations in the aerosol of from 1 to 100 times those in the liquid source[52] have been reported.

With few exceptions,[5, 9, 10, 11, 28] field studies of wastewater aerosols have equated recovery concentrations with emission concentrations without taking into account aerosol die-off, deposition, and diffusion between the source and the nearest sampling points. However, because the nearest sampling point in most of the studies was as near the source as a person might be, aerosol recovery is probably a valid assay index of emission. Knowledge of emission rates would be important in dispersion models.[10, 11]

Viable aerosol emissions from aerated wastewater, as measured by downwind recoveries, have been reported to increase with wind speed.[4, 8, 12, 16] It is important to distinguish between the effect of wind speed on emission rate and its effect on downwind recovery. Increased recoveries at higher wind speeds may have been partly a result of shorter transit time from source to sampler,[9] with less opportunity for die-off, deposition, and diffusion. However, wind action at the source may also cause a greater number of viable particles to become or remain airborne.

Other factors affecting viable aerosol recoveries near aerated wastewater have been observed. Updraft conditions in a trickling filter increased the downwind distance of the spread of the viable aerosol from the filter.[4] A greater proportion of *Klebsiella* was recovered from air near a grit chamber (raw wastewater) than from air near activated sludge aeration tanks.[9] Prechlorination (concentration not stated) seemed to have little effect on the types of bacteria recovered from air near activated sludge tanks. Viable emissions from a trickling filter seemed to increase with the size of the source[12] and the flow.[8] An upper limit was postulated for emissions, regardless of source size, when the emission rate equals the die-off and deposition rates.[10] Large plants would be expected to show less variation in viable aerosol emission rates than small plants.[10] The type of spray equipment used in the land application of wastewater is expected to affect viable aerosol concentrations downwind.[37] The effects of hard rainfall and the spraying of tank surfaces to control foam on the viable aerosol emissions have not been examined in detail, but an apparent increase in viable aerosol emissions from such spraying has been observed.[4]

The major factors affecting the emission rates of viable aerosols from wastewater seem to be whether the wastewater is aerated and what the aeration bubble size is. The spray size used in the land application of wastewater may also be an important but as yet undetermined factor. It may be practical to measure emissions in terms of viable aerosol concentrations recovered adjacent to the source, as this would be the point of initial exposure to humans. Species-selective aerosolization of bacteria may be an important factor influencing the character of the emitted viable aerosol.

Factors affecting viable aerosol survival and dispersion. Important factors in evaluating the health significance of a viable aerosol from wastewater are its survival and the range of dispersion. The principle variables affecting survival and dispersion are die-off, deposition, and diffusion.[10, 11] Several of the field investigations reviewed examined the effects of these variables on the viable aerosol. Because of the interrelationships among the factors influencing aerosol survival and dispersion and the inherent lack of variable control in field studies, the findings were generally not conclusive. However, there were some recurring similarities among the findings and other interesting observations that should be mentioned.

The general pattern observed[9] or calculated[10, 11] was a high initial viable aerosol decay rate (that is, reduction in viable aerosol concentration) followed by a much lower decay rate. The effects of the various organisms in the aerosol on the decay rate have already been discussed in the section on assayed microorganisms. Other factors apparently also exert some effect on the decay rate.

The high initial decay rate was attributed mainly to organism die-off from the stress of droplet evaporation,[10, 11] there being insufficient exposure time for factors such as solar radiation to account for the die-off. Similar findings in laboratory studies[26] and in an enclosed wastewater aeration tank,[15] in which solar radiation was not a factor, support this conclusion. The recurrent finding in several investigations of higher downwind recoveries at higher wind speeds[4, 8, 12, 16] also supports this conclusion as to the cause of high initial depletion rate, because transit time from source to sampler is decreased by higher wind speeds. However, a slower depletion of the aerosol by diffusion at the higher wind speeds may have contributed to the above finding.[49]

With two exceptions,[10, 13] air samples were collected without examination of horizontal or vertical diffusion of the viable aerosol. A single investigation[10] examined both horizontal and vertical diffusion as well as die-off and deposition rates. Die-off and horizontal diffusion were found to be the dominant factors in the depletion of the viable aerosol, the deposition of particles being important very close to the source but being less important and a nearly constant depletion factor farther than about 35 ft (11 m) from the source.

No plume-rise effect of the viable aerosol was found.[10] However, vertical diffusion was examined only to 8 ft (2.4 m) above the ground. The calculated source emission velocities of 0.8 fpm (0.24 m/min) for activated sludge aeration tanks[10, 11] and 2.4 fpm (0.73 m/min) under updraft conditions in a trickling filter,[4] in addition to the small temperature differential between emissions and ambient air, argue against significant plume rise.[49] However, the possibility of the aerosol initially rising and returning to ground level some distance downwind has not been tested in the field. No plume-rise assay was attempted in the one investigation[15] involving high-velocity stack discharge of the viable aerosol from an enclosed wastewater aeration tank.

The reported effects of relative humidity on viable wastewater aerosol survival are equivocal; some investigators have observed increased aerosol survival at higher relative humidities,[12, 13, 16] and others have found no effect.[4, 5, 10] In view of the complex relationship between relative humidity and aerosol survival extensively reported in the literature, it is not surprising that results from limited field studies were not conclusive.[10]

Viable aerosol recoveries in darkness[12, 16] were generally higher than daytime recoveries. However, reported higher nighttime relative humidities may also have influenced the recovery levels.

The addition of 0.3 and 0.6 ppm of ozone to air discharged from an enclosed wastewater aeration tank had no effect on viable aerosol recovery.[15] The effects of heavy fog, calms, and precipitation have not been examined.

An attempt was made to determine whether the geographical area of the source influenced viable aerosol recovery concentrations in the various studies. Results were compared from Massachusetts,[2] Florida,[4] Texas,[5, 9] Louisiana,[7] Oklahoma,[8,] [13,14] Ohio,[10,11] the "intermountain West,"[12,16] and New York City.[15] There simply were not enough data points available to control for the variables involved, such as environmental factors, type of treatment, and sampling procedures. Therefore, no differences in recoveries attributable to geographic area per se could be discerned. Existing differences are probably the result of prevailing environmental and other factors.

Wind speed and die-off from evaporative stress seem to be the primary factors affecting the survival and dispersion of viable aerosols from wastewater. Investigations to date have not conclusively quantified the effects of individual environmental factors on aerosol survival and dispersion. It has been shown that these effects occur very rapidly following emission from the source, that a high initial depletion rate in the viable aerosol concentration results, and that a much lower depletion rate and the prolonged survival of resistant organisms follows. Therefore, in assessing potential human exposure to the aerosols, high aerosol concentrations are applicable primarily to persons in the immediate vicinity of the sources (plant employees, visitors, and others). Much lower concentrations would apply in evaluating the exposure of nearby residents. No effect on the viable aerosol attributable to the geographic location of the source was detected from the existing data.

HEALTH SIGNIFICANCE OF FINDINGS

Viable bacterial aerosols generated from aerated wastewater processes have been recovered adjacent to the sources in concentrations as high as 1,170 viable particles/cu ft (41,200/cu m), and these aerosols have been shown to remain viable in low concentrations [generally less than five to 10 viable particles/cu ft (175 to 350/cu m)] sufficiently far downwind to reach nearby populated areas. The aerosols were in the human respirable size ranges for both upper and lower respiratory tract retention. A variety of human pathogenic bacteria genera and species attributed to the wastewater sources were recovered from air, and more frequently from downwind samples than from upwind samples. Limited examination indicated at least partial retention of virulence in recovered bacteria. The generation and spread of protein-bearing aerosols from aerated wastewater were also demonstrated without determination of aerosol viability.

Experimental results led some investigators [1,7-9,12-16] to infer that bacterial aerosols from wastewater may cause respiratory or other diseases in plant workers, nearby residents, or both. With one exception,[9] these inferences were based on qualitative considerations. On the other hand, the opportunity for atmospheric dilution of viable aerosols [2] and the relatively low viable particle concentrations recovered from air [10,32] led others to question or minimize the existence of a respiratory disease hazard.

Assessments based on literature reviews have inferred both significant [40] and minimal [41] health hazards to outdoor workers. The possibility of detrimental allergenic response from exposure to protein-bearing aerosols has been suggested.[28,29]

The health hazards of wastewater aerosols in terms of infectious doses to humans have not been examined in the field. The potential for infection of a susceptible individual exposed to a concentration of as little as one infected droplet nuclei in 500 cu ft (14 cu m) of air has been postulated.[17] Thus, the low concentrations of viable aerosols recovered from air near treatment plants may be significant to human health.

Health risks inferred from experimental field data and literature reviews were concerned almost exclusively with lower respiratory tract diseases, but three reports [12,16,26] explicitly articulated the potential for aerosol transmission of intestinal disease through upper respiratory tract retention and the subsequent swallowing of infectious particles.

Viral aerosols from wastewater have not been examined in field situations, although the presence of viruses in wastewater is well documented.[65] The existence of a virus (and also a fungus) hazard from wastewater aerosols was inferred from experimental findings on bacterial aerosols,[13,16] and the possibility of a hazardous viral aerosol from spray irrigation with wastewater has been postulated from dispersion models.[37] Long-distance aerosol transmission of viral diseases among animals and humans has been strongly suggested several times.[66-68] However, these transmissions have involved a route of "host-air-recipient" or "host-air-ground-recipient." No disease transmission by a "host-wastewater-air-recipient" route has been demonstrated.

The effects of environmental variables such as wastewater flow rate, relative humidity, and solar radiation on the health significance of wastewater aerosols have not been established; these variables apparently are not major considerations in formulating protective measures.[37,69] High windspeeds, however, are considered in formulating such measures.[69]

Historically, efforts to correlate environmental levels of airborne microorganisms with incidences of disease transmission and to assess health risks from environmental sampling have not met with success. Frequently, demonstration of the existence of an air transport route for pathogens, coupled with observation of unusual disease incidence in exposed groups, has led to the establishment of control measures even in the absence of a correlation between the two factors.

In the case of wastewater aerosols, evidence of unusual disease incidence in exposed groups (treatment plant workers) is lacking. The single health survey reported,[32] dealing with the incidence of flu, colds, and pneumonia among treatment plant workers, was inconclusive and is continuing. It is interesting to note that one of the investigators conducting this survey [32] has been the most prolific producer of published field studies on wastewater aerosols.[5,6,9,31,32] This most recent report [32] seems to herald a shift of emphasis in his outlook from aerosol studies to epidemiological studies.

The need to correlate environmental sampling results with epidemiological investigations has been suggested by others.[15,27,28,35] However, it has been pointed out that inhalation of low concentrations of airborne pathogens from wastewater may immunize treatment plant workers and nearby residents, making them unsuitable subjects for epidemiological evaluation of the health effects of wastewater aerosols.[35]

Long experience with the control of virulent aerosols has led another investigator [70] to expect that, if the hazards of wastewater aerosols were significant, unusual disease patterns among affected persons might be observed without formal epidemiological investigations.

A disturbing thought is the possible lack of awareness among U. S. wastewater works practitioners and health professionals that aerosols from aerated wastewater may be potentially hazardous. In four recent publications dealing with treatment plant operator health and safety,[33,34] wastewater aerator design,[56] and spray land application of wastewater,[69] only the last explicitly recognized viable aerosols as a factor to take into consideration. On the other hand, the development of criteria for siting wastewater treatment plants to prevent undue exposure of humans to airborne microorganisms has been recognized as a research need,[71] and the Environmental Protection Agency has identified the determination of health effects associated with land application of municipal wastewater as a research objective.[72] Also, the first sizable wastewater spray land application project near a large U. S. city was recently designed with the aerosol hazard in mind,[69] and its operation will undoubtedly be studied extensively.

For this project, the wastewater will be chlorinated before spraying. If the chlorination were completely effective, the other features would be unnecessary; however, disinfection only to less than 1,000 coliforms/100 ml is planned. Information available on this project indicated no control of viable aerosols from the initial aeration of the raw wastewater with turbine rotors. A much higher health risk from raw wastewater aerosols than from disinfected wastewater aerosols has been suggested.[74]

As an added safeguard against the production of aerosols, the wastewater will be discharged at a downward angle under low pressure to minimize the production of fine droplets,[69, 73] and the spraying operation will not be conducted during periods of high winds.[69] However, trickling filters, which also use low-pressure sprays directed downward, have been shown to produce viable aerosols.[4, 7, 8, 12, 16]

Health effects caused by airborne microorganisms from spray irrigation of crops may become an academic issue because states may eventually require disinfection of sprayed wastewater to prevent food contamination. Some states already have such a requirement.[38] If the coliform count in the liquid wastewater is used as a disinfection index, aerosols may still contain pathogenic microorganisms.

The air transport route of wastewater aerosols from their source to nearby areas, which are or may become residential areas, has been demonstrated for viable bacterial aerosols. Some evidence indicates that viruses can travel this route, and there is no contradictory evidence. The lack of evidence of disease transmission by this route precludes a firm conclusion that viable wastewater aerosols do in fact present a health hazard to plant workers, nearby residents, or persons exposed on a single or sporadic basis. Conversely, the evidence does not negate the existence of a health risk, and many investigators believe that it exists. The health implications of some wastewater processes remain unevaluated, particularly large-scale spray land application and small package-type aeration plants built closer than usual to potentially susceptible populations. Epidemiological studies should be performed to evaluate the health significance of such processes. Plant workers and nearby permanent populations may not be suitable subjects for a study of health effects because of a possible acquired immunity from repeated inhalation of low-concentration viable wastewater aerosols.

Since submission of this manuscript, three additional papers on the subject have been presented or published.[75-77] Hennessy *et al.*[75] indicate that, contrary to popular belief, low spray pressures for land application of wastewater may increase, rather than decrease, wastewater aerosol production. Although viability of aerosols was not assayed, this finding may be important to viable aerosol control procedures. The authors of the report indicate work is continuing. Dove[76] reports that the city of St. Petersburg, Fla., expects to obtain virus-free wastewater for residential lawn spraying by treating its municipal wastewater to a turbidity level of 1 to 2 JTU's, followed by chlorination, retention for 12 to 16 hr, and final chlorination of 1 to 2 mg/l. Sorber and Guter[77] have expanded on their earlier work[35] on viable aerosols from land spraying of wastewater.

ALTERNATIVES FOR FUTURE ACTIONS

Four basic alternatives for future action are to

1. Conclude the absence of a health hazard from viable wastewater aerosols on the basis of present evidence,
2. Seek further validation or negation of the air transport route of pathogenic agents from wastewater to man,
3. Seek health effects of viable wastewater aerosols by epidemiological studies and similar methods, and
4. Presume that a health risk exists and inaugurate aerosol control measures.

With the exception of the first, the alternatives are not mutually exclusive.

The body of evidence is persuasive that some as yet undetermined health effects occur from viable wastewater aerosols. There is a question of whether further environmental monitoring will yield any information not already established by past investigations, except in the case of land application of wastewater. The inauguration of extensive aerosol control measures in the absence of any evidence of real health effects seems inappropriate.

The alternative is to seek health effects in exposed susceptible groups. Appropriate groups might initially include wastewater treatment plant workers, particularly those working in enclosed aerated wastewater units and with large-scale land-spraying operations. Residents located very close to aerated wastewater sources may also be appropriate study groups. It may be necessary to study recently employed plant workers, newly arrived residents, and sporadically exposed persons (such as treatment plant tour groups) in order to discern health effects.

The effects of viable wastewater aerosols on human health should be investigated with regard to their influence in the development of both respiratory and intestinal diseases. Incidences of allergenic response, although most likely involving a much smaller susceptible population, should also be investigated.

Because it is anticipated that important health effects may be discovered, concurrent development and evaluation of potential control measures should be encouraged and should include consideration of covering aeration units and treating discharged air, alternatives to aeration processes for wastewater treatment, more effective wastewater disinfection methods for application before spraying or sprinkling, controls applicable primarily to existing facilities, and other controls applicable to spray land application.

While environmental monitoring itself is not considered to be a fruitful alternative in the study of the health significance of viable wastewater aerosols, it may be required in determining the degree of aerosol control needed for safety and the degree of control achieved by various measures. Therefore, development of a suitable index agent for assaying viable wastewater aerosols and of a practical method for determining the infectious dose and virulence of recovered airborne microorganisms may prove valuable.

CONCLUSIONS

1. The emission and spread of viable bacterial aerosols from aerated wastewater processes to areas where plant workers and nearby residents may be located has been adequately demonstrated.

2. These aerosols contain a variety of virulent, pathogenic, bacterial genera and species in particles within the human respirable size range for both upper and lower respiratory tract deposition.

3. Present evidence does not conclusively confirm or negate the existence of a health risk from viable wastewater aerosols.

4. The demonstrated potential for human exposure to viable wastewater aerosols justifies further investigation of the health effects of the aerosols.

5. This search should emphasize examination by epidemiological studies and other means of the exposed groups with due consideration of possible immunity among chronically exposed persons.

6. Potential effects include not only bacterial and viral respiratory and intestinal diseases but also allergenic response.

7. Further environmental monitoring of wastewater processes for viable aerosol production in the absence of indicated health effects is of doubtful value, an exception being the spray land application of wastewater, for which viable aerosol evaluation is needed.

8. Concurrent development and evaluation of viable aerosol control measures in anticipation of finding health effects may be valuable.

9. Wastewater works practitioners and health professionals should be made aware of the potential hazards of viable wastewater aerosols.

10. The aeration of wastewater, wind speed, and aerosol die-off are the primary factors shown to affect viable aerosol generation, survival, and dispersion from wastewater. The effects of other environmental factors have not yet been fully evaluated and may lack health significance.

11. For further environmental aerosol monitoring that may be needed, either to evaluate the need for aerosol control or the degree of control achieved by various measures, the development of a suitable index agent for assaying viable wastewater aerosols and the use of sampling procedures capable of distinguishing viable aerosol particle size spectra are recommended.

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