Aerosol Emission, Fate, and Transport from Municipal and Animal Wastes

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ABSTRACT: This review concerns the generation and fate of bioaerosols generated from the treatment of wastewater, composting plants, and during handling and land application of wastewater and biosolids. Though many bioaerosol studies have been conducted on composting and wastewater treatment plants, few studies have been conducted on land-applied biosolids. Wastewater treatment and composting plants generate almost a constant source of aerosols during plant operation, but bioaerosols tend to be contained within the plants and pose the greatest risk towards the workers themselves. Land application sites, whether wastewater application or biosolids application, are of concern as communities are beginning interface with rural areas where land application occurs. However, the majority of the available data, suggests that land application operations pose little risk towards the general public with respect to infection from bioaerosols. Aerosolized microorganisms generated by any of these land application operations appear to be inactivated relatively quickly as many are already in stressed physiological states, and the aerosol environment is also a harsh environment. Inactivation can occur via environmental dessication, ultra violet light, and oxygen radicals. In the Dowd et al., paper (2000) "worst case" scenarios during land application of biosolids predicted a risk of infection of 1.00 (100%). However an incorrect infectivity constant (r) was used in this calculation. Using the correct (r) value and more realistic values of phage:human virus ratios, the predicted risk is 5 orders of magnitude less than 1.00. In recent years biosolid treatment has improved resulting in lower pathogen concentrations, and even less potential for aerosolization. Risk that does exist can be reduced for waste-treatment workers through the use of hygienic practices, and towards the general public via the implementation of appropriate buffer zones. Overall, the risk of infection via a bioaerosol of land applied biosolid origin is low.

INTRODUCTION

THROUGH the reuse of municipal waste, in the form of wastewater, biosolids land application, and composting of sewage sludge, there exists the potential for transfer of pathogens as aerosols from the operation site to surrounding communities [40, 51]. In addition aerosols can also be generated through the operation of wastewater treatment plants or composting plants, both of which can be found within city limits or within a few hundred meters of homes. Despite the potential for aerosol generation from these operations, the risk of infection to the general public has not been well documented [40]. Bioaerosols consist of microorganisms or other biological particles such as endotoxin or peptidoglycan that become airborne, with the potential to be transported over significant lateral distances. If the microbes transported are pathogenic, then exposure to them potentially becomes a human health issue. Recently, the potential for aerosolization of pathogens from land application of biosolids has become an issue that has been debated nationally. To date, few studies on land application of biosolids have been conducted, but several studies have evaluated aerosols from wastewater treatment plants, land application of wastewater, animal manures, and composting operations. Overall, the potential for adverse health effects from pathogens in aerosols depends on their fate and transport. The fate, and inactivation of aerosolized microbes is affected by numerous environmental factors and methods of aerosol generation, while transport, or the lateral distance aerosols are carried from source to endpoint, is affected by factors such as wind direction and velocity [28, 38]. Despite the generation of aerosols, if the microbes contained within, are either inacti-

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1054-8053/01/01 013-13

vated or fail to be transported over any significant distance, is there actually a risk? This is the fundamental question that requires answer. Risk from these operations is typically thought of as being highest amongst workers that handle the waste material, but community interest in the potential for bioaeosols has recently been increasing. This review will focus on available studies and data on bioaerosols generated from wastewater treatment plants, wastewater land application, biosolids land application, and composting sites.

CHARACTERISTICS OF AEROSOLS

The term aerosol is used to describe biological particles, which have been aerosolized [28]. These particles may contain microorganisms (bacteria, fungi, viruses) or biological remnants such as endotoxin and cell wall constituents such as peptidoglycan [28]. Bioaerosol sizes range typically from 0.5 to 30 μm in diameter and are typically surrounded by a thin layer of water [49]. In other instances, the biological particles can be associated with particulate matter such as soil or biosolids, depending on the place of origin [34]. Bioaerosol particles in the lower spectrum of sizes (0.5 to 5 μm) are typically of most concern as these particles are more readily inhaled or swallowed [49].

Bioaerosols generated from the land application of biosolids may be associated with soil or vegetation depending on the type of land application. For example, if a front-end loader is used to load the biosolids spreader, it is possible that soil will be in contact with the biosolids, and therefore be associated with any aerosol generated by it. In this situation the soil particle or vegetation is known as a "raft" for the biological particles contained with the aerosol [34]. However, for soil particles to be aerosolized, the particles need to be fairly dry, and low soil moisture contents are known to promote microbial inactivation [50].

METHODS FOR AEROSOL COLLECTION

Critical to assessing the generation of aerosols is the type of sampling employed. Currently there are two main approaches that have been utilized to study aerosols: surface impaction; and liquid impingement [2, 11]. Regardless of which method is utilized, sampling is routinely done at a height of around 1.5 m above ground level corresponding to the average human breathing height [2, 18]. Normally a downwind sample is collected at a distance of between 2 and 500 m from a target point source. Typical standard sampling distances are 2, 15, and 50 m downwind, that are subsequently used to create a linear regression relating aerosol concentrations to specific distances from the point or area source [2, 20]. In most studies, samples have been collected within 50 m of the source and frequently within 20 m. In addition, an upwind (background) sample from the source is also taken to account for the normal ambient microbial air densities [2]. Samples are collected during suggested meteorological conditions that include a maximum wind speed of 6.7 m/s, and a wind direction change of less than 90 degrees within 15 minutes, although samples are collected during conditions that do not match these requirements [5]. Of these two, wind direction change is of most importance, since as wind changes direction, the direction of the aerosol plume may not be accurately represented in a downwind or an upwind sample. The entire sample collection process may be as short as a few minutes, or as long as 8 hours, depending on the sampler used and specific parameters being measured. For example, when sampling for enteric viruses or other microbes, which may be present in low aerial concentrations, it may be necessary to sample a large volume of air [39]. Advantages of using large volume samplers include, increased volume of air from 0.25 cubic meters of total air sampled using an impinger, to 1.5 cubic meters of air per minute using high volume electrostatic precipitators, although microbial inactivation may increase. Alternatively sampling precision and volume sampled can be increased through the use of multiple samplers used in an array with simultaneous measurements at discrete locations.

AEROSOL SAMPLING VIA LIQUID IMPINGEMENT

Liquid impingement typically involves collection of an air sample into a buffered liquid trapping agent such as water amended with 0.1% peptone. Air and biological particles are drawn through a single glass inlet depositing the aerosols into a solution through inertial forces, which remove the particles from the air [11]. This solution allows particle movement as the liquid is agitated during the sampling process, thus breaking apart any cell aggregates, and also allowing for a gentler impaction than that found with surface impaction. Survival of microbes is greater with liquid impingement than with solid impaction. The ability to collect microorganisms within a liquid also allows for a greater variety of microbial detection methodologies, includ-

ing culturable assays as well as molecular methods such as Polymerase Chain Reaction (PCR) or Enzyme-Linked-Immuno-Sorbent-Assay (ELISA) [1, 3, 47]. Culturable methods are simple to perform and extremely common, but it has been shown that many bacteria remain viable bun lose their ability to grow and form colonies on culturable plates, due to the aerosolization process or during the collection process [15,30]. However, this limitation can be overcome by using microscopic techniques and stains that differentiate viable organisms [30]. Molecular methods such as PCR are very sensitive since the technique detects nucleic acid sequences associated with specific pathogens. However, a positive PCR result does not necessarily indicate viability [32]. The AGI-30 (Ace Glass Inc., Vineland, NJ) was originally intended to be the unit of choice when collecting samples utilizing the impingement method, but variations of this device are also commonly used. Evaporation of the liquid buffer tends to be a problem particularly when sampling for more than 20 minutes, but this can be alleviated by using impingers such as the SKC Biosampler® (SKC West Inc., Fullerton, CA) in combination with mineral oil [35]. Mineral oil allows the collection of a sample for a longer period of time, and the detection of microbes present at lower aerial concentrations. Typical collection times are 15–30 minutes for water based buffers, and up to 8 hours for oil based buffers [35].

AEROSOL SAMPLING VIA SURFACE IMPACTION

Surface impaction is similar to impingement except a solid surface such as an agar plate is used to collect the sample. Most commonly used systems for surface impaction are the SAS 100® (Surface Air System) (Bioscience International, Rockville, MD) or the Anderson 6 stage sampler® (Anderson Instruments Inc., Smyrna, GA). The SAS system works by drawing air in through a perforated surface, and utilizing inertial forces to deposit air particles onto an agar medium [11]. The Anderson 6 stage sampler is similar in theory, except that particles are deposited onto successive stages that aid in determining the size of particles. Heavier particles deposit onto the first stage, and lighter particles bounce off this stage and travel via air currents onto successive stages. These systems allow for the direct cultivation of bacteria and fungi onto the agar surface. Although this is convenient, it does inhibit the user from utilizing multiple types of assays. If other assay methods are desired the organisms can be washed off the surface of the collection plate by a liquid buffer [44]. A major advantage of using these systems is that large volumes of air can be sampled within a short period of time for example the SAS 100®, can collect samples at the rate of 100 L/min [11].

Table 1. Factors Affecting Bioaerosol Fate and Transport.

	Potential to Affect	
Parameter	**Fate**	**Transport**
Relative humidity	Yes	Yes
Temperature	Yes	No
Wind speed	Unknown	Yes
Ultraviolet radiation	Yes	No
Oxygen concentration	Yes	No
Method of aerosol generation	Yes	Yes

FACTORS AFFECTING THE FATE OF MICROORGANISMS WITHIN AEROSOLS

Several parameters influence the fate and viability of aerosols in the environment. Physical characteristics of the aerosol and environmental factors are primary parameters involved in the survival of microbes within a aerosol. Size, shape, chemical composition, and density of the aerosol strongly influence fate as well as transport [38]. Environmental factors including atmospheric conditions also affect fate and transport (Table 1) [38]. Relative humidity has long been recognized as one of the most important factors involved in aerosol viability, and has been evaluated in laboratory studies that were able to isolate relative humidity as a single variable. Under laboratory conditions aerosolized cells of the Gram-negative *Escherichia coli* bacterium have been shown to exhibit almost 100 percent survival during conditions of low to mid levels of relative humidity, with enhanced decay at relative humidity above 80 percent [16]. The opposite is true for Gram-positive bacteria, which exhibit decay at low relative humidities [56]. In similar fashion, viruses containing a lipid envelope demonstrate increased inactivation at high relative humidity, where as naked capsid viruses exhibit increased inactivation at low relative humidity [38].

Bacterial inactivation through dehydration and desiccation processes occurs as relative humidity decreases and temperatures increases. This results from conformational changes in the phospholipid bilayer of the microbial cell wall due to a lack of cell available water [31]. In general, Gram-negative bacteria react unfa-

vorably to desiccating conditions whereas Gram-positive cells, are more able to withstand desiccation stress [36, 38]. Temperature is also known to play a significant role in microbial survival in aerosols. The effects of temperature are difficult to isolate from the effects of humidity as the two are frequently intertwined [38]. Overall, greater temperatures tend to favor microbial inactivation [17]. Bacterial membrane phospholipids and proteins are the main targets of temperature induced inactivation [38]. Viruses, which lack these membrane components tend to be more resistant to effects of temperature induced inactivation [38]. Lipid containing viruses tend to be more stable at low relative humidity, but the effects of temperature alone, are not as critical to virus survival [38]. Oxygen concentration, another important factor in microbial survival is involved in inactivation of bioaerosols through the production of oxygen free radicals [28, 38]. The effects of dessication are further enhanced by oxygen radicals that when combined with dessication, are thought to contribute to the inactivation of microbes [31]. Ultraviolet radiation can also detrimentally affect bioaerosols, with bacteria once again being more susceptible [38]. Ultraviolet rays damage DNA by forming thymine dimers; which prevents the cell from dividing and reproducing. Wind speed and direction correlate with overall transport of bioaerosols and may or may not affect viability, although this has not been well studied. Overall bacteria tend to be less stable in the aerosolized state than viruses, with the exception of spore forming bacteria, such as *Clostridium* spp [38].

TRANSPORT OF AEROSOLS

Because of the rapid dilution of aerosolized microorganisms, transport models are necessary to predict viable concentrations at distances of interest from the source of generation. Models are useful to predict the fate of pathogens which can not easily be measured in aerosolized form because of low concentrations in the aerosol or lack of methods for their detection. There are three important factors needed to model microbial fate: (1) release or emission from the source; (2) dispersion; and (3) deposition [38]. Release involves the particle's ability to break away from the source material such as liquid biosolids. Environmental forces such as wind can provide the energy to initiate the emission of a aerosol [27, 38]. Mechanical forces can also be provided in the form of agitation of the source material such as in the mechanical agitation of wastewater, mechanical agitation of biosolids, or human activity [10, 14, 18]. Energy to allow release of viruses from biosolids is particularly important since studies have shown that viruses are sorbed or embedded within biosolids and not easily released for subsequent transport [6]. Once a particle is released from its source material, the particle is subject to transport via prevailing air currents, convection, diffusion, and gravitational settling. Smaller particles below 5 μm are transported via air currents, while larger particles tend to leave the air currents and deposit onto surfaces. Other methods of particle movement include convection via temperature variations, and diffusion via concentration gradients [21]. Deposition is the actual settling of the particle and is controlled by the mass and density of the particle. Deposition onto a surface, once a particle is within the vicinity of a surface, can be controlled by low energy bonds such as Van der waals forces, and electrostatic forces, referred to as adhesion forces [38].

Models that have been commonly involved in predicting transport in the past have been based on aerosolized inert particles from either a point source or an area source. These models take into consideration release from source material, transport via air currents, and plume distribution making for a complex equation with multiple variables. The models were originally used to demonstrate the fate of air pollutants, and are limited to constant wind speeds under conditions where flat terrain is prevalent [42]. Under actual outdoor conditions this may not always be the case as wind gusts, and periods of no wind will greatly influence how and where a aerosol is transported. Historically most models have not taken into account microbial decay since the models were primarily designed for modeling inert particle dispersion [38]. Realistically, microbial decay must be applied to accurately predict the fate and transport of viable aerosols. Since different microorganisms react differently to each set of environmental parameters, microbial decay coefficients need to be calculated for each microorganism under a specific set of environmental

Table 2. Microbial inactivation-constants used in transport modeling of bacteria and viruses.

Aerosolized Microorganism	Inactivation Constant
Rotavirus	2.86×10^{-2} (Ijaz et al., 1985)
Coronavirus	2.66×10^{-2} (Ijaz et al., 1985)
Salmonella sp.	2.35×10^{-4} (Mitscherlich and Marth, 1984)
E. coli	1.92×10^{-4} (Mitscherlich and Marth, 1984)

Source: Adapted from Dowd et al (2000).

conditions. Decay (die-off) constants (Table 2) are used to predict how quickly a viable aerosol will be adversely affected during its travel time, be it seconds or minutes [38]. These constants help in predicting how far a viable aerosolized microorganism can be transported.

AEROSOLS FROM WASTEWATER TREATMENT PLANTS

Bioaerosol emissions from wastewater treatment plants (WWTP) have been evaluated in several studies due to concern of exposure to surrounding neighborhood and WWTP workers. Most studies tend to agree that the potential for aerosol formation does in fact exist, but the significance of this problem is still disputed. In a study conducted by Carducci et al. (2000), it was stated that indoor sewage washing stations contained the highest amount of airborne bacterial and viral contaminants, thus posing the greatest risk towards WWTP workers [14]. Significant sources of bacterial aerial contamination were also detected in areas where the wastewater was mechanically agitated (i.e., mechanical aeration basins). It was found that aerosols contained non-pathogenic intestinal bacteria such as coliform bacteria, but some enteric pathogens were isolated including *Salmonella enteritidis* and *Shigella boydii* [14]. It is noteworthy that these organisms have not been shown to be transmitted via inhalation, but can be transmitted through deposition on commonly touched areas in the plant such as stair rails and other inanimate objects, subsequently allowing for the fecal oral route of transmission [14].

Carducci et al. also noted that coxsackievirus B and reovirus were also recovered, which was of concern to the investigators, since these viruses do present a risk from a respiratory route of infection [14]. It was determined by the authors that WWTP workers would inhale at least 2 virus particles per 8 h work day when there was at least a 1 virus per 3 m^3 aerial concentration [14]. Reoviruses were consistently found to be present when other enteric viruses were present in this study, and were suggested as a potential indicator of aerosolized enteric viruses [14]. Fecal streptococci and coliphage have previously been thought of as being suitable indicators of WWTP aerosols, as they were found to be resistant to environmental stresses such as desiccation, heat, and ultraviolet rays [13, 18]. However, the results of a study by Carducci et al. (1999) noted that coliphage, while being an adequate indicator of enteric virus behavior in the environment, had no correlation when used as an indicator of aerial enteric viral contamination. In addition total bacteria and fecal streptococci ($P < .05$) had a significant correlation with aerial viral contamination [13]. Carducci's study has shown that enteric viral aerial contaminants could survive longer than traditional indicators, such as coliphage, coliforms, and fecal streptococci. Concentrations of enteric viruses such as, reovirus and enterovirus decreased by 15% at 50 m, whereas all other indicators decreased by more than 88%, with coliphage decreasing by 99% [13].

In a study by Brandi et al. (2000), aeration basins yielded few significant concentrations of aerosols even though they were believed to be significant sources of aerosols. This was believed to be due to the differences in types of aeration basins where mechanically agitated aerators yield aerosols and diffuse oxygenation systems yield little or no aerosols above normal ambient levels as shown in Table 3 [8]. When aerosols were created by the aeration basins they were found to contain staphylococci, coliforms, *Escherichia coli*, and enteroviruses. However, none of the staphylococci were confirmed to be *Staphylococcus aureus*. Specifically, *Staphylococ-*

Table 3. Aerial microbial densities influenced by two types of aeration systems used at wastewater treatment plants.

	2 m Downwind		10 m Downwind		Upwind
Microorganism	**Mechanical Aeration (CFU/m^3)**	**Diffuse Bubbler (CFU/m^3)**	**Mechanical Aeration (CFU/m^3)**	**Diffuse Bubbler (CFU/m^3)**	**(CFU/m^3)**
Total bacterial count	1817	222	1383	105	67
Total fungal count	2900	190	5000	106	92
Staphylococci	100	25	183	11	0
Total coliforms	967	0	367	0	0
E. coli	54	0	17	0	0

All samples collected from the same wastewater treatment plant throughout the summer during different periods of aeration system use: mechanical aeration, diffuse bubbler.
*All values reported in colony forming units/m3 air
Source: Modified from Brandi et al. (2000).

cus spp., coliforms, *E. coli*, and enterococci were found 20 m downwind of the tank, and the authors felt this posed a significant potential for aerosol exposure to WWTP workers [8]. Along with aeration basins, trickling filters have also been thought of as significant potential sources of aerosols.

This was found to be the case in a study conducted by Goff et al. (1973), who found that as wind travels over a wastewater treatment plant trickling filter, its total bacterial, and total coliform concentrations increased [27]. Multiple meteorological factors were found to directly impact the viability of microbes found within aerosols. Windspeed and relative humidity factors when analyzed together were found to be important factors in relating to aerosolized microorganisms' viability [27]. A median wind speed of about 6–10 mi/hr, combined with greater than 35% relative humidity resulted in a greater aerosol emission with greater microbial survival, as shown by greater concentrations of coliforms bacteria as relative humidity increased [27]. Deviations of windspeed, either greater or lower speeds, yielded lower aerosol emissions. Solar radiation has been shown to be a contributing factor amongst aerosols generated by WWTP, as night-time coliform and total bacterial numbers increased significantly, by at least 1 $\log_{10}/m^3$ of air as compared to afternoon samples near wastewater treatment plants [24, 27].

AEROSOLS GENERATED THROUGH LAND APPLICATION OF WASTEWATER

Although land application of wastewater could potentially result in greater creation of aerosols, depending on the method of application, it is less well studied than WWTP. Wastewater can be applied to land via three general methods [26]. Wastewater can be utilized via irrigation, in which sewage effluents are applied to land through the use of sprinkling systems at a low-rate of application. The overland flow system, allows the effluent to be sprayed over a field where the effluent, following a lateral travel distance, is collected and pooled into a collection ditch [26]. As the effluent in both these scenarios is applied via a sprinkler system, both these methods are condusive to aerosolization, whereas in high rate infiltration, effluent is percolated through the soil [26].

One study by Teltsch et al. (1977) involving wastewater spray irrigation found that when a bacterial concentration of greater than 103 cfu/ml in wastewater occurred, there was the likelihood of detectable aerosols [53]. In the same study, night-time irrigation resulted in aerosols that were found to contain at least a one log10 increase in bacterial concentrations as compared to daytime irrigation [53]. This was due to lower overall temperature, higher relative humidity, less solar irradiation, and overall more stable atmospheric conditions. The authors also stated that irrigation often occurs at night enhancing the likelihood of microbial survival in aerosols [53]. Wind speed appears to play a less significant role in land application as compared to WWTP studies, where wind speed has been shown to play a significant role in aerosol production. This may be due to the fact that these aerosols are already launched from their respective point sources by irrigation processes or spray-gun processes, whereas at a WWTP, the aerosol particle almost inevitably needs wind or another type of mechanical agitation to aid in the initial transport of the particles from the point source.

In a study conducted by Teltsch et al. (1980), pathogenic bacteria and viruses were identified in aerosols near a wastewater irrigation site, utilizing multiple sprinklers with varying effluent discharges of 1.7, 4.5, and 100 m^3/h [54]. The focus of this study was *Salmonella* and enteroviruses, which were detected at low levels in the air, despite concentrations in the effluent of between non-detection and 60 MPN/100ml, and between non-detection and 4 $\log_{10}$ PFU/L, respectively [54]. *Salmonella* sp. were able to survive in air for longer periods than coliforms, and the authors were quick to state that coliforms did not fulfill one of the main criteria of indicator organisms, this being longer survival in the environment than the pathogen in question. Although coliforms were detected in every air sample collected, they were present at concentrations less than *Salmonella* [54]. Of the identified enteroviruses: poliovirus, echovirus, and coxsackievirus B were the most prevalent, and were detectable over 100 m downwind of the point source [54]. As the distance from the site increased from 43 m to 100 m downwind, the ratio of enteroviruses to coliforms increased by about one $\log_{10}$ indicating less inactivation of aerosolized enterovirus than coliforms. At distances greater than 100 m, coliforms were no longer detected, whereas enteroviruses were still found, indicating that coliforms had increased susceptibility to inactivation during transport. This was further demonstrated in another study by Teltsch et al. (1980), where *Escherichia coli* concentrations decreased by ninety percent within the first ten seconds of aerosolization during the afternoon.

In contrast, reduction rates in the morning, demonstrated a 90% reduction within the first 100 seconds of aerosolization [55]. This was attributed to the harsher ambient weather conditions present in the afternoon, including relatively low humidity and increased solar radiation.

Camann et al. (1988) found significantly elevated microbial aerial densities at distances greater than 100 m downwind from a wastewater slow-rate irrigation site, that did not decrease until distances were greater than 200 m from the source (Table 4) [12]. It is important to note that the wastewater in use, was untreated with levels of fecal coliforms exceeding 6 log10 per 100 ml and enteric virus levels ranging from 100 to 1000 PFU/L prior to impoundment in a reservoir. The reservoir would reduce levels of coliforms by as much as 99% and viral levels to below 10 PFU/L, it was this wastewater that was aerosolized [12]. Even though concentrations of aerosols receded to background levels, the presence of wastewater generated aerosols can potentially be detected through the use of aerosol size determinations [5].

In a study conducted by Bausum et al. (1983), downwind aerosols differed from ambient aerosols not only in composition but also in size. The downwind wastewater-associated aerosols were smaller in average size, 2.44–3.03 μm versus ambient aerosols, 4.15–4.59 μm [5]. These differences can aid in the source identification of aerosol contamination. Even at increased downwind distances (>200 m), aerosolized HPC numbered near background levels. However, the aerosol droplet size distribution was consistent with wastewater-associated aerosols when compared to upwind aerosols thus allowing the authors to conclude that these aerosols were of wastewater origin. Hence an apparent "washout" of ambient microbes had occurred at these distances, where the wastewater-associated aerosols would temporarily take the place of the ambient aerosolized microorganisms [5].

Chlorination and long-term storage of wastewater can reduce microbial concentrations thus reducing aerosol potential. While chlorination of wastewater is effective in reducing enteric bacteria in aerosols, chlorine is less effective on enteric viruses, which are more resistant [4, 57]. A study conducted by Bausum et al. (1982) demonstrated that while chlorination did reduce downwind aerosolized bacterial concentrations to near background levels, coliphage was still detected at distances of 137 m downwind [4]. Long-term storage of wastewater involves the storage of the wastewater effluent in a holding tank for at least 30 days, removing up to 99% of the enteric viruses, and thus reducing potential aerosolized viruses [12, 57]. In addition to these two approaches, buffer zones have been found to be a cost effective approach to reducing exposure to aerosols. Buffer zones work by providing enough distance to be placed between the spray site and the nearest neighboring residences. These zones vary nationally and can be 65–300 m from the aerosol source, thus increasing the cost of wastewater application depending on the value of the land [57].

AEROSOLS GENERATED VIA LAND APPLICATION OF BIOSOLIDS AND ANIMAL SLURRIES

Recent increases in the extent of land application of biosolids nationally have resulted in an increased focus on the generation of aerosols produced during this process. Since the early 1980's, the amount of biosolids land applied has increased from 20% to greater than 60% of nearly 6 million dry tons applied today nationally [40, 41]. In 1999, 94% of Arizona's total biosolids were land applied, and in Southern California this num-

Table 4. An example of downwind microorganism densities caused during spray irrigation of wastewater.

	All values reported in cfu or pfu/m^3				
		Downwind samples			
Microorganism	**Ambient**	**30–89 m**	**90–149 m**	**150–249 m**	**250–409 m**
Fecal coliforms	<0.006	180.00	1.80	0.70	0.30
Fecal streptococci	0.07	140.00	16.00	8.00	0.50
Mycobacteria	0.1	0.10	0.80	0.20	0.20
Clostrtidium perfringens	0.08	9.00	1.20	1.30	0.60
Coliphage	<0.003	9.90	1.80	0.90	0.10
Enteroviruses		0.05			

cfu = colony forming units, pfu = plaque forming units
Source: Modified from Camann et al. (1988).

Table 5. Types of Applicators Used for Land Application of Biosolids.

Method of Application	Biosolid Material	Example Location
Slinger (90 feet) (Figure 1)	Cake (20% solid)	Sunnyside, Washington
Manure spreader (Figure 2)	Cake (20% biosolids)	Solano County, California
Spray tanker (Figure 3)	Liquid (8% solids)	Pima County, Arizona
Spray irrigation (Figure 4)	Liquid (2% solids)	Houston, Texas

ber exceeded 75% (unpublished data). Most land application is on agricultural land allowing nutrients found in the biosolids to be used in a beneficial manner. However, there has been increasing concern among communities and adjacent farms on the safety of this practice partially with respect to the potential for bioaerosols [40].

The aerosols generated depend, as in wastewater irrigation, on the method employed to land apply the biosolids (Table 5, Figures 1–4). Multiple methods do exist, such as the spray gun method (which is similar to the wastewater spray gun), that launches low solid content liquid biosolids into the air hundreds of feet [7]. This method is thought to create the largest amount of aerosols, as the launching will most likely disturb the biosolids enough to create the potential for aerosolized microbes [7]. Although this method of application, more recently, is limited in its use, animal wastes have been land applied utilizing this method [7]. The spray of pig slurry from this type of applicator aerosolized total bacterial concentrations between 400 and 2300 cfu/m^3 at downwind distances of between 120–150 m (this was

Figure 2. *Biosolids Spreader Operation.*

Figure 3. *Biosolids Liquid Spray Tanker Operation.*

Figure 1. *Biosolids Slinger Operation.*

Figure 4. *Biosolids Liquid Spray Irrigation .*

typically about 60 m away from the slurried area) from the source. Total coliforms, fecal coliforms, and fecal streptococci concentrations between non-detection levels to no more than 69 cfu/m^3 at downwind distances of between 70 and 170 m from the source were detected [7]. Fecal streptococci were found more frequently than fecal coliforms, but overall fecal bacteria were found infrequently in aerosols. Droplet size was generally large, with an average size of >8–10 μm. Typically a diameter of <5 μm is necessary for effective inhalation by a human being, however diameters of <2 μm deposit into the respiratory system most effectively [49]. The results of the Boutin et al. (1988) study suggested that the usage of reel-spraying guns yielded greater concentrations of downwind bacterial counts when compared to tank spreading.

A study conducted by Sorber et al. (1984) demonstrated a similar result, comparing the operation of tank spreading and high-pressure spray guns [48]. In that study anaerobic digested primary biosolids were applied by spray guns. It was this application method that allowed for the detection of total and fecal coliforms, coliphage, fecal streptococci, and mycobacteria at distances up to 50 m downwind, with a 10-fold increase over upwind levels, which were below detection limits, of total and fecal coliforms, coliphage, fecal streptococci, and mycobacteria [48].

Today spray tankers are a common way to land apply liquid biosolids (Figure 3). Sorber et al. studied the generation of microbiological aerosols created by tank truck sites. This method allows the minimal amount of dispersion of aerosols over the biosolids applied area compared to using a spray gun, and reduces the probability of aerosolizing pathogens. The tanker truck spreads the liquid biosolids close to ground level, at a height of 0.9–1.5 m, thus minimizing the aerosol dispersion effect [7, 48]. When sampling the tank truck sites, standard plate count bacteria, total coliforms, and fecal streptococci were indicative of some aerosolization. Standard plate counts were around one and two $\log_{10}$ units above upwind samples, and fecal streptococci/total coliforms were about one $\log_{10}$ above upwind samples, demonstrating a small amount of aerosol originating from the biosolids [48]. The low numbers are attributed to the minimal height above ground level that the tank sprays, thus minimizing the dispersion factor of the aerosol. In addition, sampling along a moving point source (tanker truck) proved to be difficult for the authors. In this situation, they decided to place two trios of air samplers 30 to 40 m apart from each other downwind of the truck as close as possible to the truck to create a sampling array. This enabled the samplers to assess the tanker emissions as they passed by each sampler. However, in this scenario, in effect there was only around 2–3 minutes of actual downwind sampling, with the remaining sampling time being equivalent to background sampling [48]. Sorber et al, concludes the study stating that no viruses were detected, even during a sampling event in which air samples were pooled together yielding a 1470 m^3 sample, which was assayed via cell culture. Despite the presence of enteroviruses in the biosolids at mean concentrations of 1–2 pfu/g, the authors implied that "aerosolization of viruses was not a significant problem" [48]. Overall, this study reported that: "In general, microbiological aerosols generated in the application of sludge to land as described in this study do not seem to represent a serious threat to human health for individuals located more than 100 m downwind of the sludge application site. In fact, the data suggest that microbiological concentrations of aerosols are significantly less than those at wastewater spray application sites and to date, no conclusive evidence has demonstrated an adverse relationship between aerosolized wastewater and human health." [48].

Thickened biosolids can be land applied through the usage of hopper spreader application [18, 19, 20, 43]. A study conducted in Sierra Blanca, TX monitored *Salmonella spp*., *Clostridium spp.*, coliphage, hydrogen sulfide producing bacteria, and typical indicator organisms (fecal coliforms, fecal streptococci) in aerosols [18, 19, 43]. This method of anaerobic digested class B biosolids application consists of loading the biosolids using a front-end loader onto a biosolids spreader, known as a hopper, with subsequent application to land. The greatest levels of aerosol contamination occurred during this loading operation [18, 19, 43]. At the loading sites, heterotrophic bacteria (HPC) averaged 4.5×10^6 cfu/m^3 and fecal streptococci, Salmonella spp., F^+ coliphage, H_2S producing bacteria, and *Clostridium spp.* averaged between 2 $\log_{10}$ and 3 $\log_{10}$ cfu/m^3 [18]. Background levels were between 10 to 100 times less for HPC bacteria, and non-detectable for the enteric bacteria and coliphage. The application site did not routinely produce high numbers of aerosolized microorganisms when compared to the loading site. Typical numbers at the application sites were about 10 times less HPC bacteria when compared to loading sites, exhibiting an average heterotrophic plate count of 1.4×10^5 cfu/m^3, and between 1 $\log_{10}$ and 2 $\log_{10}$ cfu/m^3 for

other parameters with the exception of fecal streptococci and H_2S producing bacteria, which were below detection. Interestingly, despite the lack of fecal streptococci detection, both fecal and total coliforms were detected with an average of 25 MPN/m^3 at the application site, but were not detectable at the loading site [18]. This could be attributed to the poor viability that coliforms exhibit while aerosolized, and the randomization of aerosol sampling. The authors conclude the study by stating that perhaps thermotolerant *Clostridium spp.* may be a more reliable indicator of aerosolized enteric pathogens, and that coliforms and fecal coliforms are less reliable [18].

Treatment which biosolids receive (i.e. anaerobic digestion, lime treatment, etc), and overall stresses that aerosolized organisms are placed under suggest that thermotolerant spore forming clostridia would be the most logical choice as an indicator of aerosolized pathogens, but the prevalence of *Clostridium perfringens* within aerosols needs additional study. *Clostridium perfringens* as an indicator is also supported by a study by the same authors who found that *Clostridium perfringens* could be ribotyped using the 16s-23s interspacer ribosomal region, and that sources of aerial pollution could be identified according to this DNA fingerprint [19].

A recent study evaluated the presence of *Staphylococcus aureus* in various types and classes of biosolids and sewage sludge across the United States. *S. aureus* could be detected in sewage, but was never detected in Class A or B biosolids. In addition *S. aureus* was not detected in aerosol samples collected from land application sites in Arizona, and California, although different types of biosolids (liquid and "cake") were applied and via different methods of application (liquid spray, and manure spreader) [46]. More recently, an ongoing study evaluating aerosols from various methods of land application of biosolids (liquid spray, spreading via manure spreader, and slinger application) across the continental United States, demonstrated low percentages, (<10% of all samples collected), of positive aerosols containing indicators such as total coliforms, coliphage, *C. perfringens*, and *E. coli* [52]. In addition, enteric viruses were rarely found in aerosols, and never further than 5 m from the site of application [unpublished data].

AEROSOLS FROM COMPOSTING SITES

In contrast to aerosols from the land application of biosolids, many studies have been conducted on composting sites. These studies have focused on aerosolized *Aspergillus fumigatus*, an opportunistic pathogen, and on endotoxin, the lipopolysaccaride component of Gram-negative bacteria [22, 23, 25, 33, 37]. In addition to these parameters, Gram-negative bacteria, total bacteria, thermotolerant actinomycetes, and immunological markers specific to these microbes have also been investigated [9, 37]. A more recent review of the literature conducted by Epstein et al (1994) concluded that the majority of aerosolized *A. fumigatus* are confined to within the composting site with off-site levels of *A. fumigatus* reaching background levels [22]. They concluded that even during mixing conditions (operations that involve the mechanical mixing of sludge and wood chips), the levels of *A. fumigatus* were about 1 $\log_{10}$ above that of background concentrations. Background concentrations were found to be between non-detection levels and 1 $\log_{10}$ per cubic meter. The review also noted that to date, no endotoxin levels surrounding composting sites have had negative effects on the surrounding neighborhoods [22]. The authors note that most detected levels of endotoxin were below the suggested safe level of 0.1 μg/m^3. The study concluded by stating that the majority of aerosolized *A. fumigatus* occurred during mixing conditions, or when the compost mixture was mechanically agitated, and that these concentrations despite being greater than background concentrations posed little risk [22].

Other studies have shown similar results with regards to *A. fumigatus*, specifically with regards to mechanical agitation of the compost piles [25, 33]. Kothary et al (1984) concluded that compost agitation would lead to increased levels of the fungal spores at distances within 50 m downwind of the compost site. Rainfall events would lead to 1 to 2 $\log_{10}$ lower levels of *A. fumigatus* within 50 m of the compost site [33]. In residential areas surrounding composting sites, the aerosol levels of *A. fumigatus* were below 50 CFU/m^3, where as *A. fumigatus* levels at control sites ranged from 0 to 2 CFU/m^3 [33].

More recent work has focused on immunological markers and health complaints of compost workers. The results of a 2000 study conducted by Bunger et al, noted that compost workers had more symptoms and diseases of the airways and skin than control subjects [9]. Increased IgG (immunoglobulin G) antibody concentrations amongst these same workers correlated to the increased exposure to fungi and actinomycetes present in compost-associated aerosols [9]. The study also compared the relative exposures amongst biowaste

collectors and compost workers. Biowaste collectors were found to have fungal, and actinomycete antibody titres similar to that of control subjects, and this correlated the relative amount of aerosol exposure to these types of microorganisms was correlated to their respective job settings [9]. Exposure to total bacteria, actinomycetes, and fungal spores increased by at least 1 $\log_{10}$ at composting plants when compared to biowaste collection sites [9].

THE RISK ASSESSMENT APPROACH TO ASSESS HEALTH EFFECTS OF AEROSOLS

The use of risk assessment models is currently the best method to estimate the risk of infection from exposure to any of these methods of aerosolization [29]. As an example of microbial risk assessment, the following calculations were made from data obtained from Dowd et al [20]. The utilization of mathematical modeling as an approach to microbial risk assessment was new and innovative, as shown by Dowd et al, but the values used to estimate risk particularly viral risk, overestimated the actual risk.

As an example of the risk assessment process, the risk calculations conducted in the 2000 Dowd et al paper will be recalculated using concentrations of human viruses in biosolids more suitable to current reported values. Values used in the Dowd et al paper ranged from 0.2 to 200 PFU/g for human enteric viruses and 10^4/g of phage, whereas current reported values in Class B biosolids are near 0.2 PFU/g, and values of F^+ coliphage are 10^5 PFU/g (unpublished data). Using these values, and an aerosolized phage estimation of 1 pfu/m^3 per 1000 pfu/g, to estimate the number of viruses/m^3 of air yields 2×10^{-4} viruses/m^3, which is 250 × less concentrated than utilizing the original values yielding 0.05 viruses/m^3 [20]. It was these values that were used to back calculate the rate of aerosolization, using the point/area source models (Figure 5), of viruses/s, and subsequently used to predict the concentration of viruses/m^3 at specific downwind distances under specific wind speeds [20]. Using these new values, downwind concentrations of viruses/m^3 of air are 250 × less than that of the values originally calculated. For example an originally predicted value using the point source model was 7.5×10^{-3} viruses/m^3 during wind speed of 20 m/s at a downwind distance of 100 m, but through current calculations, this value becomes 3.00×10^{-5} viruses/m^3. This value is then used to establish the number of viruses inhaled/hr exposure, utilizing the equation $N = X$ 0.83 E, where N = the number of viruses inhaled, X = concentration of viruses/m^3, E = time of exposure (hr), and 0.83 is the amount of air inhaled (m3) by the average person/hr [20]. Thus the number of inhaled viruses corresponding to a 24-hour exposure is 5.98×10^{-4} viruses. The viral risk of infection is described by utilizing the one hit exponential model, $P = 1 - \exp(-rN)$, where P is the probability of infection, r describes the virus ability to infect and overcome host defenses (r = 0.0253), and N is the inhaled number of viruses (5.98×10^{-4} viruses) [29]. Thus the risk of infection from a 24-hour exposure to land application of biosolids under a constant 20m/s wind speed would yield a 1.51×10^{-5} risk of infection. Compared to previous calculations, as calculated by Dowd et al, this infectious risk is 5 orders of magnitude less than the reported 1.00 risk of infection. It is important to note that an incorrect (r) value of 39.5 was used, whereas the correct (r) value is 1/39.5, yielding 0.0253 (45). Correctly using this (r) value and using virus downwind concentrations predicted by Dowd et al. yields a risk of 3.76×10^{-3}, which is nearly 3 orders of magnitude less than that of the reported value of 1.00 using the same criteria (100 m downwind, 20 m/s windspeed, and 24 hr exposure).

CONCLUSIONS

It is clear from this review that aerosols can be generated during wastewater treatment, land applied wastewater, land applied biosolids, and composting sites. Bioaerosols generated by wastewater treatment plants, and composting plants, may not contribute to health effects in the surrounding community, as the majority of the aerosols generated by both plants are maintained to within the site. In addition, some modern wastewater treatment plants and composting plants are currently being built as enclosed structures. This suggests that the majority of aerosols generated at each plant may contribute to the health effects of the workers and handlers only, and to a lesser extent the general public. Hygienic practices need to be employed to reduce the health risks related to work in such an environment. Simple practices, such as the wearing of gloves, washing of hands, and eye protection can minimize direct inoculation of pathogens into the body. Within enclosed wastewater treatment and composting plants, exposure can also be minimized by the usage of air filters in areas of great mechanical agitation. Overall the risk of infection from bioaerosols generated at a wastewater treatment plant, or at a composting plant is low.

Wastewater irrigation or liquid biosolid land application can produce aerosols, as these methods result in an aerosol being launched a number of feet into the air particularly with wastewater spray irrigation. Wastewater irrigation is generally considered to be the more likely to result in aerosol production, while liquid biosolid land application utilizing a tank truck is considered to be of minimal risk. In addition, the aerosols created by spray of wastewater will more easily be deposited within the lung, and enhanced travel is seen with these droplets when compared to the much larger and denser aerosol droplets produced by biosolid spray. Spreading of "cake" biosolids also creates aerosols, but it seems that the loading of these spreaders creates more aerosols than the actual land application. The amount of microorganisms being launched by loading events leads to increased numbers of aerosols in the area surrounding the loading site, but overall transport of these microbes over great distances has been shown to be unlikely. Overall, land application of biosolids would appear to create minimal adverse public health affects with respect to aerosols. Overall, the risk of infection from aerosols generated during land application of biosolids is low.

Once again, as with wastewater treatment and composting plants, the health risk seems to be greater for the workers themselves than for the general public. Therefore common sense hygiene practices should be encouraged in these situations, the use of particulate blocking masks, gloves, and most importantly hand-washing. However exposure also can be minimized through the use of buffer zones, chlorination, storage of wastewater, application during daylight hours with ultraviolet light and dessication acting as methods of disinfection, application devices which minimize aerosol production, usage of higher quality biosolids/wastewater, and application during low wind velocity conditions. To date, few data are available on aerosol production during land application of biosolids, and most studies have relied on measurements of bacterial indicators and phage surrogates. Data on enteric pathogens is sparse, particularly with regard to viruses, thus the need for more research with currently employed techniques such as polymerase chain reaction. There exists multiple research articles on the presence of aerosols from wastewater treatment plants, composting plants, and wastewater land application, but still the need for a comprehensive look at the generation of aerosols from the land application of biosolids using multiple methods of application needs to be investigated, as this is the area of waste reuse that is garnering the most amount of interest as housing communities are beginning to intrude on land application sites.

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