COMPOSTING CRITERIA FOR ANIMAL MANURE

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PRODUCE SAFETY PROJECT

Background

Manure that has undergone appropriate treatment to inactivate human pathogens can be a safe soil amendment for use in agriculture. However, incomplete treatment of manure can lead to survival of human pathogens that could contaminate produce in the field and, ultimately, lead to foodborne-illness for those who eat the produce.

Composting involves decomposition of organic matter by microorganisms that create a humus-like material for use as a soil amendment. Advantages to composting include:

- improving soil structure and thus encouraging root development and making the soil easier to cultivate;
- providing plant nutrients to soil that enables the increased uptake of nutrients by plants;
- aiding water absorption and retention by the soil;
- binding of synthetic agricultural chemicals and thus minimizing contamination of groundwater supplies; and
- substantial reduction, if not elimination, of pathogenic microorganisms.

Disadvantages of composting organic material include:

- loss of nutrients, such as nitrogen, during the process;
- the significant time, equipment, labor, and land required for composting; and
- offensive odors generated during composting.

Composting may occur under both aerobic (involving large amounts of oxygen) and anaerobic (involving the absence of oxygen) conditions but the organisms involved in the former system generate substantial amounts of heat while the organisms in the latter system do not. In either system, materials that may be included for decomposition are yard trimmings, wood chips, food scraps, municipal solid waste, and animal manures. The focus of this document will be on aerobic composting of animal manures.

Copious amounts of manure are generated in animal production. For example, beef and dairy cows produce between 12 and 23 tons/year, whereas chicken broilers and layers produce 66 and 95 pounds/year, respectively [*1*]. In 2009, USDA reported that about 15.8 million acres of cropland, equivalent to about 5% of all U.S. cropland, are fertilized with livestock manure [*2*]. Animal manure is a well-documented source of zoonotic pathogens (harmful microbes carried by animals that cause illnesses in humans), such as *Escherichia coli* O157:H7, *Salmonella* spp., and *Cryptosporidium parvum*. Animals may carry these pathogens without showing symptoms, and may also have sporadic fecal shedding [*3*] that

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contributes to the difficulty in discerning their presence in the animal's gastrointestinal tract and hence fecal matter. In the case of *E. coli* O157:H7, for example, its prevalence in fecal samples of beef cattle feedlots varies from 1.3-7.5% of individual animals [*4*, *5*]. Moreover, a significant portion of the infected animals (9%) are high shedders (with $>10^4$ cfu/g *E. coli* O157:H7) [*5*]. High pathogen loads are troublesome as these microbes can survive in manure and manure-amended soils for months to years and can subsequently contaminate waterways via runoff or vegetables grown in these soils [*6*, *7*]. Given the increase in outbreaks associated with the consumption of raw fruits and vegetables during the past two decades, there is concern that manure may serve as a source of pathogens to these commodities.

Although most manure generated in agriculture is applied directly to land where there is low risk for contact with produce (*e.g.* corn), aerobic composting of manures may be conducted before application to accelerate the destruction of zoonotic pathogens. In this process, the manure is mixed with one or more carbon amendments to produce a nutrient-rich environment favorable for the metabolism of thermophilic microorganisms. Heat generated from the metabolic activity of these microbes plays a major role in the inactivation of zoonotic pathogens but the time for heat generation and subsequent pathogen inactivation depends on the composting system and its management. The three typical types of composting systems include:

1. passively or actively aerated static pile systems;
2. windrow systems in which the compost feedstocks are mixed into narrow trapezoidal elongated rows and turned systematically on a regular schedule; and
3. in-vessel systems in which a constructed containment structure houses the compost feedstocks and is equipped with some means of forced aeration.

In this document, the focus of the discussion is primarily on static and windrow piles since in-vessel systems are not employed as often. Ranging in scale, from as little as one static pile on a farm at which the manure is generated to large-scale public, private, and institutional windrow operations, these differences in scale create disparities in the ability of operators to monitor the effectiveness of pathogen inactivation. For the most part, commercial compost operations, including those incorporating animal manures, are regulated by the states; however, no permit is required for operation in some states. Hence, operations distributing finished product within those states or non-commercial operations in regulated states are not directly subject to regulatory oversight that includes time-temperature guidelines for proper composting.

Furthermore, based on several surveys involving pathogen testing of commercial composting facilities and packaged compost materials, existing time-temperature criteria may not always be adequate to assure pathogen-free compost. As an example, a survey of 72 commercial facilities conducted in the 1990s revealed that the finished composts from more than half of the facilities were contaminated with *Salmonella* spp. despite meeting the time-temperature criteria [*8*]. In a more recent survey, 6.7% of 108 commercial compost samples exceeded the EPA *Salmonella* standard (3 most probable numbers (MPN)/4 g of compost dry weight) [*9*]. Improper management during composting may explain why the pathogen survived; however, failure to detect *Salmonella* in the finished compost is not evidence that the composting process was conducted properly as the pathogen may not have been present initially, and the sample size and number are generally too small to be statistically valid.

To provide a better understanding of the physical and chemical conditions contributing to pathogen inactivation during composting, this paper reviews

the intrinsic and extrinsic properties of the composting process. In light of this information, this paper will discuss the current standards for composting animal manures and their inherent weaknesses as well as the lack of uniform composting standards both domestically and internationally. Finally, it provides recommendations for expansion of these standards or guidelines and a short discussion of the areas in which additional research is needed.

Intrinsic and Extrinsic Properties of the Composting Process to Control Foodborne Pathogens

The primary factor responsible for inactivation of foodborne pathogens during aerobic composting of animal manures is heat; thus, developing and holding of temperatures above 55°C (131°F; 3 days for static piles or bioreactors and 15 days for turned windrows) has been considered the minimum threshold for this purpose. In addition to temperature, other chemical, biological, and physical factors during composting also influence pathogen inactivation. Examples include volatile acids, ammonia, microbial competition, drying, and UV light. Aerobic composting of manures is a complex process but typically starts by mixing one or more carbon amendments with a nitrogen-rich material to produce a nutrient-rich environment favorable for the growth of microorganisms. The compost material is then placed into piles, windrows, or containers that provide a sufficient mass for self-insulation. During composting, the process follows a predictable succession of stages. During the initial stages when temperatures are 35 to 45°C, mesophilic bacteria (bacteria that grow best at temperatures from 30 to 45°C) predominate and their metabolic activity may be accompanied by a decrease in pH due to the accumulation of volatile organic acids, such as acetic and lactic acids. When organic acid levels decline and the pH begins to increase due to the production of ammonia, the temperature increases (50 to 70°C) and marks the thermophilic stage during which thermophilic microorganisms (microorganisms that thrive at an optimal growth temperature of 55 to 75°C) dominate. If oxygen levels become low or the temperature approaches 70°C at any time during this active composting period, the temperature will decrease because microbial activity declines. Turning the pile or applying forced aeration, however, will revitalize the system and temperatures will increase again. Another consequence of heat generation is that moisture is removed from the compost heap and surfaces become drier. Eventually, the microbial activity slows down and the temperature will decrease and stabilize. A curing or maturation period then follows the active composting stage. During this period, compost material continues to be broken down but at a much slower rate by the dominant microbial community of fungi and actinomycetes [*10*].

One of the major characteristics of composting systems that affects pathogen inactivation is temperature and moisture stratification [*11*], and this characteristic would be accentuated during winter composting. A gradation of temperature zones exists from the interior (high temperatures, moist conditions) to the exterior (ambient temperature, dry conditions) and thus a gradation in the population of surviving pathogens also occurs. Interestingly, significant correlations between moisture content and the temperature distribution within compost piles have been reported [*12*]: when the moisture content is high, the high-temperature zone extends closer to the surface than when the moisture content is low. The status of these conditions is significant because moist heat, in general, is more destructive to pathogens than dry heat. To circumvent disparities in stratification, turning of compost heaps is often recommended in order to expose the material to the

thermal temperatures. In one mathematical model, it was predicated that at least three turns are required for windrow composting to ensure that less than 0.2% of the raw material remained in the 'cold' part of the heap [*13*]. An overlooked weakness of this solution, however, is that recontamination of interior portions from contaminated sites (i.e. surface compost material or turning equipment) would occur during turning of the material.

In the absence of turning, the contribution of chemical and physical factors, other than heat, are more dominant in pathogen inactivation at sites near the surface of compost piles. For example, in slightly acidic compost systems (pH ~ 5.5 to 6.0), inactivation of both *Salmonella* spp. and *Listeria monocytogenes* occurred with very little increase in temperature and was attributed to an increase in volatile acids [*14*, *15*]. Ammonia generated during composting is another chemical that has bactericidal properties [*16*]. On the surface of compost piles, pathogens are exposed to solar radiation and very dry conditions, either of which can result in their inactivation [*17*].

An implicit assumption made with time-temperature guidelines for pathogen inactivation is that inactivation is not dependent upon the rate at which that temperature is achieved. Extended exposure to non-lethal temperatures above 40°C, however, has been shown to generate heat-shock proteins that aid in the survival of the organism at higher temperatures [*18*]. Such conditions may have occurred in those cases where pathogens were detected in finished composts that were determined to have received the appropriate time-temperature conditions.

Differences in the amounts of heat generated among compost systems are in large part dependent on the feedstocks incorporated into the compost preparations [*19*]. In general, raw materials are blended to an initial moisture content of 40 to 60% and a carbon:nitrogen (C:N) ratio of 20:1 to 40:1 to serve as nutrients for the types of microbes that produce the most desired form of compost. Carbon amendments vary in their availability to microorganisms. For example, carbon from cellulose within straw is much more available to microorganisms than is the carbon from lignin within woody materials. Hence, compost heaps made with straw will heat more rapidly than those made with wood chips. Even when the same carbon amendment is used, differences in heat generation can occur when the carbon becomes more available through increases in the amendment's surface area. Similarly, the carbon in older feedstocks would likely be more readily available due to microbial decomposition that already has occurred to some extent. Manure stockpiling, prior to composting, can also affect the rate of heat generation during composting as the nutritional composition of this material for compost microbes would have changed from its initial fresh state. Since composting may include a very diverse group of feedstocks with a wide range of nutritional constituents affecting microbial metabolism, it would be difficult to avoid situations in which pathogens can be exposed to temperatures conducive to their production of heat-shock proteins.

A critical component to the breakdown of organic materials and subsequent generation of heat in compost systems is the non-pathogenic indigenous microflora that metabolize available nutrients. Manure and not the carbon amendment, is the primary source of the microbial community [*20*]. In general, high microbial diversity is considered fundamental for an efficient and satisfactory composting process; however, differences in microbial composition exist among manures. For example, in poultry-manure compost, the bacterial community is comprised of a more divergent group of species that utilize a more diverse group of substrates than the microbes associated with cattle-

manure compost [*21*]. In spite of these differences, ample levels and diversity of microflora are present in manure such that commercial inoculants, (non-pathogenic microbial cultures added to the green compost) and accelerant chemicals (ammonium sulfate) rarely affect the thermophilic phase of the composting process [*22*].

In addition to metabolic heat generated at interior locations of compost piles, indigenous microflora may also affect the fate of pathogens in compost mixtures through other mechanisms. These include production of antimicrobials like lactic acid or bacteriocins. Moreover, the role of antimicrobials may be more important when heat does not play a dominant role, such as at surface locations or compost that is curing, i.e. in the later stages of composting when relatively little heat is generated. Pathogen populations when present in compost typically represent only a small fraction of the total microbial population. As a result of this imbalance, pathogens are at a competitive disadvantage compared to the total microbial population, especially when available growth nutrients are limited at the later stages of composting. Indigenous microbes may also affect pathogen survival through the production of antimicrobial agents; in one study, the growth of *Salmonella* was suppressed in non-sterilized composted biosolids compared to sterilized samples [*23*].

Another factor in the composting process that would affect the survival of pathogens is the external environment under which composting occurs. Composting operations typically take place outdoors where they are subject to a wide range of uncontrolled environmental conditions, including rainfall and wide temperature fluctuations. Although there is concern that pathogens will leach from compost piles to surrounding land and waterways during rain events, the potential for cross-contamination of pathogen-free compost material at inner sites of piles, with pathogens residing at non-heated surface sites of compost heaps, should also be of concern. In addition, for most composting operations, sufficient barriers are not in place to prevent vermin and insects (pathogen vectors) from contacting pathogen-free compost during the curing stage.

Current Microbiological and Hygiene Criteria for Composting and their Inherent Weaknesses

Composting criteria throughout the world are promulgated by a variety of organizations, both public and private. Addressed in these criteria are concerns not only regarding pathogen and heavy metal levels in the finished product, but also concerns regarding liquids leaching from compost, odor, vectors, dust, noise, security against illegal dumping, protection of surface and groundwater, and neighborhood compatibility. In this document, discussion will focus primarily on the microbiological criteria that composted materials containing animal manures should meet.

Within the United States, composting of animal manures is not specifically regulated by a federal agency. In the absence of a federal standard, commercial compost operations that utilize animal manures as a feedstock are generally subject to state and local regulations that vary dramatically in their scope and complexity. Included in these regulations are criteria regarding the size of the operation that must seek a permit and requirements for product testing and record keeping of feedstocks and operational parameters, however, the specific requirements for each of these criteria often differs among states. As for hygienic criteria, states largely defer to the federal specifications described in 40 CFR Part 503 that is administered by the Environmental Protection Agency (EPA) for regulating land application of Class A composted

sewage sludge. These criteria include both end-product and process criteria. For Class A standards, it is stipulated that either the density of *Salmonella* spp. in the compost must be less than 3 MPN/4 g of compost dry weight or the fecal coliform density must be less than 1,000 MPN/g of compost dry weight. Process requirements to generate a Class A compost consist of a minimum temperature of 55°C (131°F) for 3 days in aerated static piles or in-vessel systems or 15 days in windrow systems during which the material has been turned five times. Comparison of time-temperature conditions to other country requirements reveals microbiological criteria that are both stricter and more lenient than the Part 503 limits. In general, there is considerable agreement that temperatures higher than 55°C and below 65°C have the desired effect, although the duration for which the temperature must be achieved varies with the country as well as with the type of compost system [*24*]. Austria is unique in that it relies solely on end-product testing for *Salmonella* spp. and *E. coli* and does not specify a time-temperature minimum, although it still requires that temperature be recorded each day during the thermophilic phase.

The National Organic Program, administered by the U.S. Department of Agriculture, includes a composting standard as described in 7 CFR Part 205.2: it requires that plant and animal materials have an initial C:N ratio of between 25:1 and 40:1. The time and temperature standards are the same as those described for Class A composted sewage for static, in-vessel and windrow systems. This standard, however, is not an enforceable safety standard, subject to government enforcement. Rather, it applies only to those operations who sell to growers that wish to carry the "USDA Organic" label on their crops.

Due to the complexity of regulations that exist among states, a number of organizations offer independent verification programs through which compost producers can assure consumers that quality claims (*e.g.* compost maturity) have been verified. On a state-level, the California Compost Quality Council Organization is one example of an alliance of compost producers, scientists, farmers, landscape contractors, and recycling advocates formed to administer compost quality guidelines for the state. On a national-level, the United States Composting Council administers the Seal of Testing Assurance (STA) program, a compost testing and information disclosure program that is based on the laboratory manual "Test Methods for Examination of Composting and Compost" (TMECC). Similarly in the United Kingdom (UK), its national composting trade organization, the Association for Organics Recycling (AFOR), administers the British Standards Institution's (BSI) Publicly Available Specification (PAS) 100 certification program. As a component to these certifications, the STA and the BSI PAS 100 programs provide expanded coverage beyond what is described in the regulatory statutes, detailing the mechanisms by which compliance of hygienic standards and process guidelines may be documented. These programs provide greater consistency in the interpretation of the technical requirements for producing a safe product; however, as discussed below, gray areas still exist.

One of the critical points to meeting EPA's hygienic process requirements is that each and every particle of compost material must be subject to the time-temperature criteria. In the case of uncovered static piles, this requirement is impossible to achieve because the surface temperatures never increase more than a few degrees above the ambient temperature. EPA's answer to this dilemma is to *recommend*, not require, that a 0.3 m (1 foot) or greater layer of insulating material such as finished compost be placed over all surfaces of the pile [*25*]. In contrast, the USDA National

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Organic Standards Board addresses temperature stratification in static piles by vaguely stipulating that the piles must be mixed or managed in some manner to ensure that all feedstock heats to the required time-temperature [*26*]. Incorporating a mixing (turning) step, however, negates the static nature of the system and changes it to a modified windrow system. Discounting that there may be recontamination of the sanitized material with pathogens that survived in the cooler layers, there is an inherent assumption that in turning the compost material, all material on the surface will inevitably end up at some time in the core and exposed to the target temperature for a period of time. For example, when the target temperature is 55°C, EPA requires that windrows be turned five times. More frequent turning, however, may be warranted when high moisture contents, observance of noxious odors, or temperature decreases occur in the windrows. The BSI PAS 100 standards offer another option of only turning twice, but in this case the target temperature is 65°C. This number of turns may be sufficient when machinery that has been designed for that purpose, such as windrow turners, is used. However, when using equipment such as front-end loaders for mixing of static piles, there are no required or recommended mixing strategies provided to ensure that the initial surface material is entirely exposed to the interior at some point. Instead, the mixing strategy is left to the skill and judgment of the individual operating the machinery. Inefficient mixing by an operator may have factored into the observation that as many as 12-15 turnings were necessary to reduce pathogens in windrow composted sewage sludge in the Los Angeles County Sanitation District [*25*]. Given that there is no test to assure the efficiency of the turning operation, it represents a weakness in the regulations and standards.

To document that time-temperature hygienic process criteria have been met during composting, operators must monitor the temperatures in their compost mixtures. This activity is accomplished by a variety of methods, ranging from hand-held temperature probes inserted manually into the compost mixture at specified sampling times to thermocouples placed inside the compost mass, with temperatures automatically logged on a recording device at designated intervals.

According to EPA, temperature monitoring should be conducted at the same time each day during the thermophilic phase of composting in order to demonstrate that the material has been subjected to 55°C for the required period of time. In addition, all areas of a batch or pile should be represented during temperature monitoring to ensure that temperature profiles from multiple points in the process are meeting minimum temperatures. In the case of windrows in which pathogen inactivation is expected to occur at the core, only core temperatures need to be monitored. For aerated static pile and in-vessel composting processes, temperatures should be taken at multiple points at a range of depths throughout the composting medium, especially at points which are likely to be cooler than the center of the pile. Unfortunately, these guidelines are vague and therefore, in most cases, the number and locations of temperature measurements is at the discretion of the composting operator. The one exception is for UK operations seeking BSI PAS 100 certification. Their criteria indicate that temperatures should be monitored at the core of turned windrows every 250 m^3 of compost and at the surface, core, and basal areas every 250 m^3 in aerated static piles. However, even these criteria provide the composting operator the flexibility to bias the outcome. For example, temperature measurements taken at sub-surface locations in the middle of the day and on the south side of a pile would likely be higher than those taken at night or on the north side of a pile. Since a compost operator has some

flexibility in when and where temperature measurements are taken, there could be differences in whether time-temperature conditions have been met.

Finished-product testing provides additional assurance that compost mixtures prepared with animal manures are safe for application to fields where produce that will be eaten raw is grown. Although it establishes a certain level of safety of the final product, spot testing does not serve to establish the efficiency of the composting process in pathogen inactivation, unless it can be shown that pathogens were present in the initial materials. Variable components of end-product testing include: number of sub-samples taken, location at which sub-samples are taken, sample size, and frequency at which batches in composting operations are sampled. In sub-sampling, the objective is to adequately represent the system under investigation. In the STA program, no less than 15 point samples should be taken from areas of the compost pile that are representative of the general appearance and are not excessively moist (> 60% moisture). The formula used to estimate a statistically valid number of sub-samples by the BSI PAS 100 system is $n = 0.5(V^{1/2})$ where V is the volume of the batch or sampled portion of production. Based on this formula, the number of sampling points varies from 12 to 30 with distribution of these points throughout the sampled portion as follows: for bulk materials, incremental samples are taken from the top, middle, and bottom zones and throughout the length and width of the pile, ignoring material nearer than 50 mm (2 inches) to any surface. Alternatively, during loading and discharge of the material, samples may be removed from a moving stream of product. If compost material has been packaged, each sampling point shall be in a different randomly selected package. The sampler should avoid removing any material from the sample to give it superior physical traits as deliberate bias would have been introduced and the sample would no longer represent the bulk or batch of interest. As compost heterogeneity increases, the number of sub-samples should be increased. Sample size will also depend on the heterogeneity of the mixture, however, according to the TMECC, the minimum volume for pathogen analysis, when sub-samples have been composited, is 1 to 4 L. To complete a full suite of analytical procedures (physical, biological, and chemical tests), however, approximately 12 L of compost material are needed. As for the frequency of sampling, it is considered neither practical nor cost-effective to test every batch of compost produced.

For state agencies and organizations adhering to the EPA recommendations, the required frequency of monitoring ranges from once a year for facilities producing small amounts of compost (< 290 metric tons) to once a month for facilities producing larger amounts of compost (> 15,000 metric tons) [*27*]. The U.S. Composting Council has a slightly different scale for determining frequency of sample testing: once a quarter (1-2500 tons) to once a month (>17,501 tons). BSI PAS 100 requires that certified composting operations submit samples once every calendar year, or every 5000 m^3 of compost produced (whichever is soonest) [*28*]. At present, renewal of certification under the BSI PAS 100 scheme requires that the three most recent samples pass all obligatory parameters. AFOR is considering a percentile approach where an occasional sample failure would be tolerated without jeopardizing a facility's certification status. From a safety perspective, however, there should be more emphasis on evaluating whether the frequency of testing is adequate. It is recognized by AFOR that their minimum testing requirements were developed without the benefit of knowing the likely variability of the measured parameters and therefore represented a best guess at the optimum level

of testing required to ensure that the compost produced was of adequate quality, without placing an undue financial burden on producers. A recent review of compost test data from 467 tests for *E. coli*, however, revealed only an 80% pass rate [*29*]. Given this record, there may be many more substandard batches that would not have been tested but would have been distributed and used.

One of the advantages to monitoring the relative levels of an indicator microbe, such as *E. coli*, is that they are abundant in manure and, in the absence of pathogens, may be used to validate the efficiency of the thermophilic composting process. This premise has been based on the observation that reduction in fecal coliforms correlated to reduction in *Salmonella* sp. when biosolids were composted [*30*]. Based on this relationship, EPA requires that only measurement of either *Salmonella* spp. or fecal coliforms be conducted. In contrast, Canada and the UK require that *both* the target levels of *Salmonella* and the indicator be met [*28,31*]. This requirement may provide different outcomes depending on how long after the thermophilic phase the compost is sampled. If measured shortly after the maximum temperatures were reached in the compost, levels of both *E. coli* and fecal coliforms would likely be low, in line with very low levels or the absence of *Salmonella*. If measured several weeks after peak heating, however, regrowth of these indicator bacteria may occur and therefore their levels would not be indicative of *Salmonella* populations if the pathogen had been eliminated completely during the thermophilic phase [*32*].

Utilizing microbial indicators to characterize the pathogen inactivation efficiency of composting in all types of manure-based compost systems should be applied with caution despite the allure that tests for pathogen indicators can be less expensive than tests for pathogens. In the case of compost systems containing cow manure, *E. coli* has been documented to be a good indicator of the inactivation of *E. coli* O157:H7 [*33*], similar to that observed in compost of human waste sludge. In contrast, it has been determined that *E. coli* is not a good indicator in compost systems containing chicken litter because inactivation of *E. coli* did not coincide with that of *Salmonella* [*17*]. Monitoring *E. coli* levels in swine manure may not be a valid measure of thermal inactivation of noroviruses as very little inactivation occurred during the thermophilic composting phase that would have inactivated a large portion of the *E. coli* population [*34*]. The use of fecal coliforms as a pathogen indicator of composted materials also has its limitations due to the diverse groups of microorganisms detected by the assay. Although *E. coli* is one of the major bacterial types contributing to fecal coliform numbers in manures and freshly mixed compost, it has not been the major group in stored thermophilic-treated composts [*32*]. Instead, regrowth of *Klebsiella*, another bacterial genus that is detected in the fecal coliform assay but largely originating from carbon amendment feedstocks, is dominant in the latter material. These differences in bacterial composition of the fecal coliform group between the raw materials and the finished compost would lead to inaccurate conclusions regarding potential pathogen contamination of the finished compost.

Considerations for Improving Composting Practices Involving Animal Manures to Enhance the Microbiological Safety of Compost

Based on the limitations in the current standards that have been described above, improvements to standards and regulations that would provide greater assurance of the microbiological safety of composted materials containing animal manures are needed. At this point in time, however, changes

to current time-temperature process guidelines are not advocated as more stringent guidelines to ensure inactivation of heat-shocked pathogens might prove excessive. Instead, other improvements should be implemented on a routine basis to generate a microbiologically safer compost and thus provide greater public-health protection.

One improvement would be requiring insulating covers to be applied to both aerated static piles and windrows. Currently, the description provided by EPA for construction of static aerated piles recommends application of a 0.3 m (1 foot) or greater layer of cured compost or other insulating material. In one study evaluating *E. coli* O157:H7 inactivation at surface sites of finished compost from covered (0.15 or 0.3 m depth) and uncovered heaps, the pathogen was detected in the uncovered heaps through 120 days whereas it was below detectable limits after 21 days of composting in covered heaps [*35*]. In most compost certification programs, however, insulating covers are neither a standard requirement nor their use suggested as a routine practice in composting by windrow systems. Insulating covers would help ensure that all compost material is subjected to the thermophilic conditions necessary for inactivation of pathogens and would avoid reliance on the practice of turning to place all compost particles in a position that would receive heating conditions sufficient to kill pathogenic contaminants. Caution should be used in selecting insulating cover material and the depth of the layer applied so that there is sufficient oxygen transfer to interior sites of the heap.

Once the thermophilic phase of composting is complete, compost materials continue to decompose but at a much slower rate in what is known as the curing phase. The primary advantage of this stage is stabilization of the compost with remaining nutrients incorporated into microbial metabolic products. A benefit from a safety standpoint is inactivation of residual surviving pathogens through competitive antagonism by the active diverse microbial community. Inclusion of a minimum curing period into the criteria for composting animal manures could increase assurance of the safety of the product. Evidence to support this approach is based on the survival of *L. monocytogenes* in immature composts and lack of detection in mature composts [*36*]. However, additional studies addressing the survival/inactivation of pathogens during this phase are needed before recommending specific time periods for the curing phase. Curing of compost can be problematic if pathogens regrow because the microbial community is not of sufficient diversity to outcompete the pathogens for nutrients. Typically, pathogen regrowth does not occur; however, the conditions that enable regrowth are not easily measured using routine assays. Development and application of a microbial inoculum that would be active competitors of pathogens during the curing stage could ensure that regrowth would not occur. In the event that such a biological treatment is developed, it could be included as an essential process component.

Inactivation of pathogens in manures through aerobic composting is dependent on multiple physical, chemical and microbial factors that are often beyond the control of the compost operator. When manure feedstocks are considered to be heavily contaminated with pathogens, it should be standard practice to process these materials with intervention technologies that provide for more effective operational control. Examples include: lime treatment (sufficient quick lime or hydrated lime is added to raise the pH to 12 for ≥ 2 hours of contact) or heat/steam processing (temperature of compost exceeds 80°C to reduce moisture content to 10% or lower) [*25*].

Management of composting operations should not be overlooked as an important component in producing a safe compost product from animal manure. For example, facilities that provide barriers to separate actively composting heaps from cured heaps are less likely to encounter cross-contamination events. Hence, standard operating procedures (SOPs) for composting operations should detail how contamination risks are controlled and managed on a day-to-day basis. Included in these procedures should be verification on a yearly basis of the accuracy of equipment (*e.g.*, temperature, pH) used to monitor the composting system as well as a record of the weather conditions observed during the composting process. To emphasize the critical nature of food-safety protocols, BSI PAS 100 updated in 2005 its criteria to require compost operations to submit for review its SOPs along with its quality assurance plan and a hazard analysis critical control point (HACCP) program. Implementation of these protocols would then be verified by an inspector for the certification body during an on-site visit. Adoption of HACCP systems throughout the composting industry would further raise the bar for enhancing the safety of compost materials prepared with animal manures.

Knowledge Gaps

Composting of organic materials is a practice that has been conducted for hundreds of years; however, knowledge gaps still exist with regards to composting conditions that lead to heat-shocked pathogens, which are more difficult to inactivate by heat, and the time-temperature conditions needed for their subsequent inactivation. Another issue that has not been adequately addressed is the potential for migration of pathogens, especially those surviving on the surface of compost heaps, to within compost piles when exposed to rain. Changes implemented in compost processing to address non-microbiological issues of concern, such as odor reduction, will also have to be evaluated for their effect on pathogen survival and inactivation. Continued screening of potential indicators of process control or pathogen contamination would be valuable toward developing improved assays for documenting compliance of food safety programs. Furthermore, additional mitigation strategies are needed to kill pathogens when compost materials do not comply with microbiological criteria.

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