GUIDANCE MANUAL

Best practices and strategies for pathogen-free compost production

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Rationale

Composting is a natural process that converts organic waste into a nutrient-rich material known as compost. It is economically viable since it cuts the cost associated with the hauling of wastes and enables farmers to reduce the use of fertilizers. It is an environmentally friendly and sustainable approach to waste management, offering numerous benefits, such as waste reduction, soil enrichment, and greenhouse gas reduction. The utilization of compost as a sustainable alternative to chemical fertilizers promotes organic farming practices, reduces reliance on synthetic inputs, and contributes to the overall health of an ecosystem. Composting plays a crucial role in the circular economy, where organic waste is recycled back into the soil, closing the nutrient loop.

Although composting is a magical process that has been in use for a long time as part of waste management, consumers are still worried about composting and the quality of the compost, mainly because of pathogens including, bacteria, viruses, and parasites that can be present in organic waste and pose potential health risks if not properly managed during the composting process. The risk of pathogen contamination in compost is a valid concern as it can lead to outbreaks of diseases. Moreover, when individuals fear the potential health risks associated with compost, they may be less likely to use it as a soil amendment or fertilizer. In fact, sometimes gardeners would sterilize compost before using it but this practice is also not feasible as it may lead to the killing of beneficial microbes from compost. Therefore, it is important to continuously improve strategies for reducing pathogens in composting.

The main way pathogens can be eliminated from compost is through heat. Usually, during the composting process, high temperature is attained which is sufficient to eliminate all pathogens. However, this has not been happening as observed during the *recent study conducted by CSE in few composting sites*. Report data showed a very high number of *E.coli*, faecal coliforms and *Salmonella*.

This condition may have occurred due to improper operation management practices that need to be rectified. Therefore, understanding and implementing effective pathogen removal techniques are vital for ensuring the production of high-quality, safe compost. The purpose of this report is to provide an overview of the removal of pathogens from compost, highlighting the importance of pathogen reduction for safe and effective composting practices.

This report will delve into the various methods and technologies used to eliminate or reduce pathogens in compost, including temperature-based processes, composting additives, and post-composting treatments. It will explore the scientific principles behind pathogen reduction, discuss the factors influencing the effectiveness of pathogen removal methods and analyze their advantages and limitations.

Furthermore, the report will examine the regulatory frameworks and guidelines governing composting practices, both at the national and international levels. It will highlight the importance of compliance with regulations to ensure the production of pathogen-free compost that meets the required quality standards.

Overall, this report aims to provide a comprehensive understanding of the removal of pathogens from compost, and its significance in sustainable waste management and agricultural practices. Exploring the scientific, regulatory, and environmental aspects of compost will contribute to the knowledge base and promote the adoption of safe and efficient composting methods for a greener and healthier future.

Composting as a sustainable waste management technique

Definition of composting

Composting is an environmentally friendly way of reducing organic waste. It is a controlled process that mimics the natural decomposition of organic matter in a way that optimizes microbial activity and nutrient cycling. Composting creates an ideal environment (air and water) for beneficial microorganisms to break down organic materials (greens and browns) into a stable, humus-like substance that can be used to improve soil fertility and support plant growth.

Composting options include the following:

- Windrow composting: The material to be composted is formed into long piles that are typically triangular or trapezoidal in section and 1.25–2.5 m in height with a width-to-height ratio of roughly two to one. The piles must be large enough to retain heat and ensure that thermophilic conditions are reached, but are porous enough to allow oxygen flow to its core. Windrows must be turned at regular intervals to maintain porosity and allow oxygen into the core of the windrow.
- Aerated static-pile composting: The material to be composted is placed in piles, typically around 2 m deep and covered with 150–300 mm of finished compost or another suitable material to reduce heat loss. Blowers are used to pump air into the piles through pipes laid under the piles. The use of aeration removes the need for labor to turn the compost. Additionally, the forced aeration controls the process better and the time needed is generally lower than for turned windrow composting. However, these systems are more expensive than turned windrow systems and require good maintenance systems, an effective supply chain, and a reliable power source.
- In-vessel composting: The material to be composted is placed in enclosed reactors with systems to control temperature, moisture, and odours. Commercial in-vessel composters are expensive and relatively complex and are unlikely to be suitable for treatment plants in lower-income countries.

Till date, most initiatives to compost municipal solid waste have used windrow composting.

Benefits of composting:

1. **Waste reduction and diversion:** The process of composting assists in keeping organic waste out of landfills, where it would otherwise contribute to the creation of a powerful greenhouse gas—methane. The amount of organic waste delivered to landfills and the resulting environmental effects are decreased by composting organic waste, since it recycles important

nutrients back into the soil.

2. **Soil enrichment:** Compost is a highly nutritious soil amendment that promotes water retention capacity of the soil, develops better soil structure and enhances nutrient availability. It adds organic matter to the soil, increasing its ability to hold moisture and reducing erosion. The essential nutrients such as nitrogen, phosphorous and potassium that are present in compost support plant growth by enriching the chemical, biological and physical properties of the soil.
3. **Improved soil health:** Compost improves soil health by encouraging a broad and active soil microbial community. Compost's microbes decompose organic material, liberating nutrients and fostering an advantageous environment for plant roots. Better soil aeration, drainage and nutrient cycling are the results of the altered soil structure and elevated microbial activity.
4. **Reduces water pollution and soil erosion:** Using compost helps in avoiding soil erosion by strengthening the soil's structure and enhancing its capacity to hold water. This preserves the water quality and aquatic ecosystems by reducing the flow of silt and contaminants into water bodies.
5. **Carbon sequestration and climate change mitigation:** Composting aids in reducing the effects of climate change as it stores carbon content in the soil. Compost contains carbon and, when added to the soil, helps increase the soil's organic carbon reserves. Increased amounts of soil organic carbon aid in long-term carbon storage, which lowers the atmospheric concentration of carbon dioxide.
6. **Sustainable agriculture:** Compost promotes sustainable agricultural practices by reducing reliance on synthetic fertilizers and pesticides. It provides a natural source of nutrients, improves soil fertility and supports healthy plant growth. Compost application can enhance crop productivity, reduce the need for chemical inputs and contributes to the overall sustainability of agricultural systems.

Importance of pathogen removal in compost

Pathogen elimination in compost is crucial for several reasons. Firstly, if pathogens are not effectively controlled during the composting process, they may remain in the organic waste products. This poses a serious health risk as these pathogens can then be transferred to crops, gardens or other areas where the compost is used, potentially causing illness in humans or animals.

Secondly, compost that contains many pathogens is not considered safe for use in agricultural or horticultural practices. If contaminated, the pathogens can infect plants, leading to crop failure or reduced plant health. This can have serious economic implications for farmers and gardeners.

The following main factors make pathogen elimination crucial for composting:

1. **Public health protection:** Pathogens found in compost can cause serious health dangers if not properly handled. When pathogens are inhaled, swallowed or come into touch with exposed wounds, they can cause diseases and infections. Composting that does not adequately eradicate pathogens may spread of diseases among composting practitioners, adjacent populations, or people using the compost for gardening or agricultural purposes.
2. **Worker safety:** Pathogen removal is crucial for ensuring the safety and well-being of workers involved in composting operations. Composting facilities often employ individuals who handle the organic waste, turn the compost piles and manage the overall composting process. Proper pathogen removal practices protect these workers from exposure to harmful microorganisms, minimizing the risk of occupational health hazards.
3. **Consumer confidence:** The availability of pathogen-free compost instills confidence in compost users who use it for gardening, landscaping or agriculture. Compost is expected to be a safe and dependable soil supplement that promotes healthy plant growth while avoiding the introduction of dangerous microorganisms. Pathogen elimination increases trust and stimulates the use of compost in several applications.

4. **Environmental protection:** Pathogens in compost have the potential to pollute soil, surface water and groundwater if not controlled appropriately. Pathogens can be introduced into the environment by runoff from compost piles or the use of contaminated compost, potentially damaging ecosystems, water quality and sensitive creatures. Pathogen removal practices that are effective protect the environment from potential contamination and promote sustainable waste management practices.
    - **Water contamination:** Pathogens can affect water bodies through runoff or leaching. This can happen if the compost is not properly handled or applied. Rainwater runoff from compost piles, as well as the usage of contaminated compost near water sources, can transmit pathogens into surface or groundwater, possibly degrading water quality and causing threats to aquatic ecosystems and public health.
    - **Soil contamination:** Inadequately processed compost or compost that contains persistent pathogens, can introduce these microorganisms into the soil. Pathogens can survive and persist in the soil, potentially infecting plants or entering the food chain through crops. Soil contamination by pathogens can pose risks to agricultural productivity, plant health and food safety.
    - **Ecosystem disruption:** Pathogens from compost, if released into the environment, can disrupt natural ecosystems. They may impact soil microorganisms, beneficial insects and other organisms that are crucial for ecological balance. Imbalances in microbial communities and the introduction of non-native pathogens can have cascading effects on ecosystem health and biodiversity.
5. **Regulatory compliance:** Pathogen reduction standards for composting facilities have been specified in many jurisdictions' rules and guidelines. Following these requirements guarantee that compost manufacturers adhere to the essential health and safety standards.

Compliance with regulations help to avoid potential legal ramifications and promote appropriate waste management practices.

6. **Quality assurance:** Pathogen removal is a key aspect of ensuring the overall quality of compost. High-quality compost should be free from harmful pathogens to support healthy plant growth and minimize the risk of disease transmission. By implementing effective pathogen removal measures, compost producers can maintain consistent quality standards and deliver a safe and reliable product to their customers.

Pathogens in compost: types and sources

Common pathogens found in compost: Compost can indeed harbor a wide range of pathogens such as bacteria, viruses and parasites. The presence of these pathogens in compost is influenced by the organic materials used and the composting method employed. The specific types of pathogens may vary from one compost batch to another. Bacterial pathogens commonly found in compost include *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes*. These bacteria can cause foodborne illnesses and are commonly associated with fecal contamination. Viral pathogens like norovirus and enteric viruses have also been detected in compost samples, posing a potential risk of infection.

1. **Bacterial pathogens:** Pathogenic bacteria are frequently isolated in high numbers in the compost feedstocks and sometimes, in finished composts. According to the USEPA (1992), the bacteria that draw the most concern are *Shigella sp., Salmonella sp.,* and *Yersinia sp., with salmonellae* being the most frequently studied because of their frequent occurrence in feedstock materials. They cause severe illness relatively often, and are easily and reliably quantified.[1] The major bacterial groups that are commonly found in the compost are discussed as follows:

- **Faecal coliforms:** The presence of coliform bacteria is often used as an indicator of the overall sanitary quality of soil and water environment. Coliforms are considered as the indicators of pathogen presence as they are more resistant, present in large numbers, and easily quantifiable in comparison to other microorganisms. There is extensive data indicating that the densities of faecal coliforms are good indicators of the effectiveness of the composting process in destroying enteric pathogens. Using an indicator such as coliforms, instead of disease-causing organisms, is indeed advantageous. Indicators like coliforms occur at higher frequencies compared to pathogens and are also easier and safer to detect. These are mostly non-pathogenic and occur naturally in organic waste in high numbers (10^4–10^6 CFU per gram), and thus can be analyzed without additions to the material.[2]

- ***Escherichia coli (E. coli)*:** *E.coli* is a thermotolerant, faecal coliform that is predominantly found in the faeces of warm-blooded animals. Both pathogenic and non-pathogenic strains of *E.coli* can be present in fecally contaminated compost samples. The non-pathogenic strains of *E.coli* and faecal coliforms are commonly used as indicator organisms. Pathogenic *E. coli* tend to be present in faecal materials in much smaller quantities than non-pathogenic varieties. Studies found that toxigenic *E. coli* represented only a small proportion (an estimated 0.3 per cent) of the total faecal coliform population. Pathogenic strains of *E. coli,* such as *E. coli O157:H7*, can cause severe gastrointestinal illness that may be lethal if not treated properly. Recent study (see Table 1: *Load of indicator and pathogenic organisms in compost in CSE study on compost*) conducted for the compost obtained from 23 composting sites of three Indian states, Haryana, Uttar Pradesh and Odisha, showed the presence of faecal coliform and *E.coli* up to 10^5MPN/g.
- ***Salmonella and Shigella.*:** *Salmonella* and *Shigella* is considered the major problem when it comes to the hygienic quality of compost.[3] This is probably because these bacteria are ubiquitous and have a capacity for very fast growth. *Salmonella* is the most common foodborne pathogen and results in 93 million cases of

salmonellosis and 150,000 deaths every year, globally. A recent CSE report inspected 23 different composting sites in Indian states and found the presence of *Salmonella spp.* up to the range of 10^7MPN/4g indicationg a high level of contamination *(See Table 1: Load of indicator and pathogenic organisms in compost in CSE study on compost)*. Hassen et. al., 2001 reported that various species of *Salmonella* named as *Salmonella enteritidis, S. hadar, S. braenedrup, S. corvallis, S. menchen, S. newport, S. virchow,* were detected during composting. Although all strains of *Salmonella* bacteria are not lethal (non-typhoidal *salmonellae*), these strains can cause salmonellosis, a foodborne illness characterized by symptoms like diarrhea, fever and abdominal cramps. However, a few strains such as *S. Typhi, and S. Paratyphi* (typhoidal salmonellae) may cause severe illness characterized by an onset of high fever with abdominal pain and general malaise.

Table 1: Load of indicator and pathogenic organisms in compost in CSE study on compost[4]

Location	Faecal coliform (MPN/g TS)	*E. coli* (MPN/g TS)	*Salmonella* (cfu/g TS)
Gurugram, Haryana	$0.3 \times 10^1 - 4.3 \times 10^5$	$0.3 \times 10^1 - 1.7 \times 10^5$	$0.3 \times 10^1 - 1.7 \times 10^7$
Agra, UP	$0.3 \times 10^1 - 2.0 \times 10^2$	$0.3 \times 10^1 - 1.2 \times 10^2$	$4.5 \times 10^2 - 1.7 \times 10^6$
Odisha	$1.5 \times 10^1 - 2.5 \times 10^4$	$0.1 \times 10^1 - 1.2 \times 10^4$	$8.5 \times 10^3 - 2.8 \times 10^7$

CSE's report, Quality assessment of compost produced in different locations of Haryana, Uttar Pradesh and Odisha

- **Other bacteria**
  - *Listeria monocytogenes*: Listeria can cause listeriosis, which can lead to severe infections, especially in individuals with weakened immune systems.[5]
  - *Faecal streptococci: Faecal streptococci* are commonly considered as the best indicators of faecal pollution. They are more resistant to different environmental factors than coliforms. They are essentially represented by *Streptococcus faecalis, S. faecium* and *S. bovis*.
  - *Staphylococci*: These are ubiquitous bacteria and *Staphylococcus aureus* is one of the main causes of collective toxic infections from food. This species also causes cutaneous infections that represent a risk for compost handlers and agriculturists during farm compost spreading. It liberates a thermostable enterotoxin. The evolution of *Staphylococci* during the composting cycle is similar to that of *Streptococci*.

2. **Viral pathogens:**
   Norovirus: Norovirus is a common cause of gastroenteritis, leading to symptoms like vomiting, diarrhea and stomach cramps.
   Rotavirus: Rotavirus is a leading cause of severe diarrhea in young children and can be transmitted through contaminated compost.

3. **Parasitic pathogens:** Two types of parasites can be present in compost feedstocks: the single-celled protozoans and helminths, or worms.

- **Protozoa**
  Faecally contaminated feedstock materials often contain pathogenic protozoa of varieties including *Giardia lamblia, Entamoeba histolytica, Cryptosporidium spp.* and others. These parasites can cause gastrointestinal illness, particularly in individuals with weakened immune systems.
- **Helminth**
  Helminth ova are of particular concern in compost

for a number of reasons. Firstly, they are frequently isolated in feedstocks of faecal origin and can be present in relatively high numbers. Secondly, they are very resistant to a variety of chemical and physical agents. This is especially true at temperatures below 50.8°C, and attempts to correlate indicator organism reduction to helminth levels in this temperature range over-predict helminth reduction. The persistence of helminth ova is illustrated by the fact that *Ascaris, Trichuris, and Toxocara* ova have been reported to remain viable in soil for several years, with one study reporting *Ascaris* infectivity even after 15 years in soil. Thirdly, helminths, like protozoa and viruses, have a very low infective dose; ingestion of a single egg poses a significant health risk. *Ascaris* is a type of roundworm that can be present in composted animal manure and may cause gastrointestinal infections. For these reasons, their reduction to levels below detection is desired.

4. **Fungal pathogens:** Several opportunistic fungal pathogens are also presented in Table 1. However, fungi are not enteric in origin and produce adverse health effects via inhalation or skin contact, rather than as a result of ingestion. Risk is thus much greater to compost facility workers, who are in close contact with airborne compost dust, than to the general public.[6] Hence, fungal pathogens in compost are not considered in compost regulations in the United States (USEPA 1999), WHO and FCO. However, one pathogen one does need to be aware of is *Aspergillus fumigatus*. This is an airborne pathogen that thrives in high temperatures, although populations drop rapidly after that. This can cause respiratory problems. It tends to attack those with an illness such as asthma, or those with a compromised immune system. If that applies to you, it's worth taking extra care.

Health risks associated with pathogens

The following are key health risks associated with pathogens. Table 2 summarizes the pathogens and the disease associated with them:

1. **Infectious diseases:** Compost pathogens can cause infectious diseases in humans and animals. Bacterial infections due to *E. coli*, *Salmonella*, and *Listeria monocytogenes*, as well as viral pathogens such as norovirus and rotavirus, can be transferred by contact with contaminated compost or through inhalation of pathogen-containing aerosols. These infections can cause gastrointestinal problems, respiratory infections and other systemic problems.
2. **Allergies and respiratory issues:** Composting activities that emit airborne pathogens and particulate matter can cause respiratory difficulties, allergies and asthma in people who are sensitive. Microorganisms and their metabolites in compost can cause respiratory irritation and allergic reactions, particularly in workers or those who are frequently exposed to compost dust.
3. **Zoonotic diseases:** Pathogens originating from animal waste, such as feces or manure, can be present in compost and pose the risk of zoonotic diseases. Zoonotic diseases are infections that can be transmitted between animals and humans. For example, the bacteria *Campylobacter* and *Cryptosporidium*, commonly found in animal waste, and can cause gastrointestinal illnesses in humans.
4. **Occupational hazards:** Composting facilities can pose a higher risk for workers in terms of exposure to pathogens. These workers can be at greater risk of work-related infections due to various factors. Contact with contaminated compost, which can contain harmful microorganisms, can lead to skin infections. Additionally, the process of composting can result in the aerosolization of pathogens, increasing the risk of respiratory problems for workers who breathe in these particles. Furthermore, workers may come into contact with contaminated surfaces, which can potentially transmit pathogens and cause gastrointestinal ailments.

Table 2: Pathogens found in compost feedstocks and associated diseases (adapted from Wichuk et al., 2007)[7]

Group	Organism	Associated diseases
Bacteria	*Arizona hinshawii*	Arizona infection
	Bacillus anthracis	Anthrax
	Bacillus cereus	Gastroenteritis
	Campylobacter jejuni	Gastroenteritis
	Clostridium botulinum	Botulism
	Clostridium perfringens	Gangrene, gastroenteritis
	Escherichia coli and other coliforms	Gastroenteritis, diarrhoea and internal infections
	Leptospiraicterohaemorrhagiae	Haemorrhagic jaundice
	Mycobacterium tuberculosis	Tuberculosis
	Pasteurella pseudotuberculosis	Pseudotuberculosis
	Pseudomonas aeruginosa	Gastroenteritis
	Salmonella (~1700 types)	Salmonellosis (food poisoning), gastroenteritis
	Salmonella typhi	Typhoid fever
	Shigella (4 species)	Shigellosis, bacteria/bacillary dysentery, gastroenteritis
	Streptococcus spp.	Gastroenteritis
	Vibrio cholerae	Cholera
	Yersinia sp.	Yersinosis, acute gastroenteritis (incl. diarrhea, abdominal pain)
Viruses	*Adenovirus (31 types)*	Conjectivitis, respiratory tract infections, gastroenteritis
	Astroviruses	Epidemic gastroenteritis
	Caliciviruses	Epidemic gastroenteritis
	Enteroviruses:	
	Coxsackie virus	Aseptic meningitis, gastroenteritis, hepatitis, fever, cold-like symptoms etc
	Echovirus	Aseptic meningitis, paralysis, encephalitis, fever, cold-like symp- toms, diarrhea, hepatitis, etc
	Poliovirus	Poliomyelitis
	Hepatitis virus	Infectious hepatitis
	Norwalk and Norwalk-like viruses	Epidemic gastroenteritis with severe diarrhea
	Reovirus	Respiratory infections, gastroenteritis, diarrhea, common cold, hepa- titis
	Rotavirus	Gastroenteritis, infant diarrhea, acute gastroenteritis with severe diarrhea
Protozoa	*Balantidium coli*	Balantiasis, diarrhea, and dysentery
	Cryptosporidium parvum	Gastroenteritis, cryptosporidiosis
	Dientamoebafragilis	Dienamoeba infection
	Entamoebahistolytica	Amoebic dysentery, ameobiasis, acute enteritis

Group	Organism	Associated diseases
	Giardia intestinalis	Giardiasis
	Giardia lamblia	Giardiasis (incl. diarrhea, cramps, weight loss)
	Isopora belli	Coccidiosis
	Naegleriafowleri	Meningoencephalitis
	Toxoplasma gondii	Toxoplasmosis
Nematodes (Helminth)	*Ancylostomabraziliense*	Cutaneous larva migrans (creeping eruption)
	Ancylostomacaninum	Cutaneous larva migrans
	Ancylostomaduodenale	Hookworm, Ancylostomiasis
	Ascarislumbrioides	Ascariasis, digestive disturbances, abdominal pain, vomiting, rest- lessness, roundworm infestation
	Ascarissuum	May produce symptoms such as coughing, chest pain, and fever
	Enterobiusvermicularis	Enterobiasis, pinworm infestation
	Necatoramericanus	Hookworm
	Strongyloidesstercoralis	Strongyloidiasis
	Toxocaracanis	Visceral larva migrans, fever, abdominal discomfort, muscle aches, neurological symptoms
	Toxocaracati	Visceral larva migrans
	Trichuristrichiura	Trichuriasis, abdominal pain, diarrhea, anemia, weight loss
Cestodes (Helminth)	*Diplylidiumcaninum*	Tapeworm infection
	Echinococcusgranulosus	Unilocular echinococcosis (hydatid disease)
	Echinococcusmultilocularis	Alveolar hydatid disease
	Hymenolepis nana	Taeniasis (tapeworm infection)
	Taeniasaginata	Taeniasis, nervousness, insomnia, anorexia, abdominal pain, diges- tive disturbances
	Taeniasolium	Taeniasis, nervousness, insomnia, anorexia, abdominal pain, diges- tive disturbances
Fungi	*Aspergillus fumigatus*	Lung mycosis, Aspergillosis
	Blastomycesdermatitides	Blastomycosis
	Candida sp.	Systemic and skin mycoses, Candidiasis
	Coccidiodesimmitis	Coccidioidomycosis (San Joaquin fever)
	Epidemophyton sp.	Skin mycosis
	Histoplasmacapsulatum	Histoplasmosis
	Micromonospora spp.	Farmer lung
	Microsporum sp.	Skin mycosis
	Sporothrixschenkii	Sporotrichosis
	Trichosporoncutaneum	Skin mycosis
	Tricophyton sp.	Skin mycosis

Sources of pathogens in compost materials

The presence of pathogens in compost can be attributed to the inclusion of contaminated organic materials. Common sources of pathogens in compost materials include:

1. **Food waste:** Food waste, including discarded fruits, vegetables and kitchen scraps, can introduce pathogens into compost. Contaminated food items such as spoiled products or improperly handled food, may carry pathogens that can survive the composting process. *Salmonellae* comes commonly from food wastes, essentially from poultry, meat, milk and its derivatives, as well as some wastes, especially poultry waste.

2. **Animal manure:** Animal manure such as cow, horse or poultry manure, is a valuable source of nutrients for composting. However, it can also harbor pathogens if the animals have been exposed to infectious diseases or if the manure is not properly managed.

3. **Yard waste:** Yard waste such as grass clippings and leaves, is commonly included in composting. While it is less likely to introduce pathogens compared to food waste or manure, contamination can occur if the yard waste has been in contact with animal feces or other sources of pathogens.

4. **Sewage sludge:** Sewage sludge, also known as biosolids, can be used in composting operations. However, it requires careful treatment and monitoring due to the potential presence of pathogens from human waste.

Compost quality standards for pathogens

Table 3: National and international regulation for pathogens in biosolids/compost reuse

International regulation for pathogens in bio solids/compost			
Pathogens	**USEPA (Class A Biosolid)**	**WHO**	**FCO[8]**
Faecal coliforms	< 1,000 MPN/gram of total solids (dry weight basis)	–	--
Salmonella spp.	< 3 MPN/4 gram of total solids (dry weight basis)	–	--
E. coli	---	< 1,000/gram total solids	--
Pathogens	--	--	NIL
Enteric viruses	Density of enteric viruses ≤1 PFU (plaque forming unit) per 4 g of total solids (dry weight basis)	--	--
Viable helminth ova	Density of viable helminth ova ≤1 per 4 g of total solids (dry weight basis)	≤1 egg per gram of total solids	--

Management of factors affecting pathogen survival and persistence

Table 5 summarizes the parameters involving the composting process along with their optimum levels and mitigation approach. The major factors by which the survival and persistence of pathogens in composting systems are influenced have been explained as follows:

1. **Temperature:** Studies showed that *Salmonella* growth was found to occur in compost, in spite of competing coliforms and other bacteria, optimally in the mesophilic temperature range (20–40°C). However, high temperatures achieved during the composting process plays a crucial role in pathogen inactivation. Thermophilic composting, where temperatures reach 55–65°C (131–149°F), is effective in killing many pathogens. Extended exposure to these temperatures is necessary to ensure thorough pathogen removal. Table 4 highlights the temperature and time criteria by USEPA for pathogen-free composting.

Table 4: US EPA temperature and time criteria for composting

Composting Type	Requirement
Windrow composting	Temperature must be >55°C for at least 15 days and windrows must be turned at least five times
Aerated static pile or vessel	Temperature must be >55°C for at least 3 days

2. **Moisture content:** Pathogens require moisture to survive. Maintaining the appropriate moisture level (40–60 per cent) in a compost pile promotes microbial activity and decomposition while limiting pathogen survival. Excessive moisture or waterlogged conditions can enhance pathogen persistence. However, the final ready compost should be properly dried and have a minimum amount of moisture as studies have shown that the microbial population regrowth in compost piles occur when the moisture content was more than 20 per cent.

3. **C/N ratio:** C/N ratio is considered to be the consistent indicator for pathogen removal during composting and regrowth in ready compost as carbon is a rate limiting factor. The carbon-to-nitrogen (C/N) ratio affects the composting process and can influence pathogen survival. Maintaining an optimal C/N ratio (between 25:1 and 35:1) facilitates microbial activity and decomposition during composting, that contributes to pathogen reduction. This is because of the availability of optimal proportion of carbon and nitrogen for microbial growth that leads to the breakdown or decomposition of organics in waste material. This results in the increase in temperature and lowering of the C: N ratio that leads to auto sterilization of all kind of microbes from the ready compost. So, if C: N ratio of waste is less than 25:1, then carbon-rich organic material (dry leaves) can be added into the source waste material during composting. Higher C/N ratios may be reduced by adding biodegradable material having high

nitrogen content, such as non-edible oil cakes, green biomass, etc. On the other hand, a C/N ratio of more than 15:1 in the ready compost may lead to the gradual start of pathogen regrowth in compost piles.

4. **Composting time and turnover:** Longer composting durations and regular turning of compost piles promote pathogen reduction. Adequate time allows for the breakdown of organic matter and the depletion of available resources for pathogens. However, too much turning frequency also breaks the maintenance of thermophilic phase. One of the studies revealed that reduction of faecal coliform (FC) and faecal *streptococci* (FS) was found to be highest during a turning frequency of every 24 hours during a 20 days composting cycle. However, reduction of FC and FS was found to be comparatively low, with a turning frequency of every six hours, 12 hours, and 18 hours. This was because a 24-hour turning frequency caused the longest thermophilic phase (four days) with a higher rise in temperature (58°C), thereby leading to pathogen inactivation.[9]

5. **Composting system design:** The design and management of composting systems can impact pathogen survival. Factors such as aeration to maintain oxygen levels, insulation to maintain temperature and the use of composting additives can influence microbial activities and the overall effectiveness of pathogen reduction.

Table 5: Summary of parameters affecting the composting process along with their management approach (modified from Amuah et al., 2022)[10]

Parameter	Range	Description	Mitigation approach
Moisture level	< 45%	Low moisture retards the composting process	Regulate moisture levels by adding H_2O
	45 to 60%	Ideal range	
	>60%	Reduced oxygen level Displaced moisture Causes anaerobic conditions	Improve turning or add low moisture content materials
Oxygen level	< 5%	Low oxygen level Excessive moisture Retards evaporation Causes anaerobic conditions	Add materials with high moisture Reduce the particle size of the materials (improve porosity) that enhance evaporation
	13 % to 18 %	Optimum range	
	>18%	Excessive oxygen level A drop in temperature Excessive evaporation Retards decomposition	Add dry materials/large sizes
pH	< 5.5	Causes excessive organic acid	Add materials with high N until a suitable C/N ratio is obtained
	5.5 to 8	Ideal pH	
	> 8	Excess nitrogen is reached	Materials with high C contents may be added
Particle size	< 3.1 mm	Compaction of materials Small pores Causes anaerobic conditions	Turn the pile Add large sixe material
	3.1–12.7 mm	Ideal range	
	>12.7 mm	> Excess aeration Drastically reduces temperature	Reduce material size by chopping/shredding
C/N	<25:1	Excess N level produces odour overheating of pile.	Incorporate materials with high C content
	25:1 to 40:1	Ideal C/N	
	> 40:1	Excess C Cooling composting system Retards composting	Add materials with high N levels

Parameter	Range	Description	Mitigation approach
Temperature	<35°C	Insufficient moisture Reduces microbial and metabolic activities N deficits Low C/N ratio A high C/N ratio inhibits microbes from producing enzymes	Wet the material/ add materials with high moisture Add materials with high N
	35- 40°C (mesophilic phase)	Ideal range for microbial growth and decomposition	
	50-65 °C (Thermophilic phase)	Ideal for pathogen inactivation	
	> 65°C	Poor ventilation Low moisture	Turn the pile Add materials with high C levels

Pathogen removal processes in composting

Several methods such as thermophilic composting, vermicomposting and pasteurization can be implemented for the efficient removal of pathogens. These methods have been explained below:

Temperature-based methods:[11] There are the following mechanisms (heat, competition for resources and microbial attack to pathogens and antimicrobial properties) by which pathogens get eliminated from compost.

- **Heat:** Thermophilic composting requires four key things—oxygen, moisture, the right mix of materials and **heat-generating microorganisms.** Once established, the compost pile will naturally heat up as it undergoes thermophilic decomposition, with temperatures reaching as high as 60–65°C. This high heat kills off weed seeds and harmful pathogens, leaving behind a valuable, nutrient-rich material that can be used to improve soil health and support plant growth.

The Science Behind It

1

What is Thermophilic Composting?

It's the process of using heat-loving microbes to decompose organic materials. The temperature in a thermophilic pile usually ranges from 120°F to 160°F

2

Factors Affecting the Composting Process

The success of a compost pile depends on many factors such as moisture, carbon-to-nitrogen ratio, oxygen, temperature, and particle size.

3

Benefits of Thermophilic Composting

It kills weed seeds and plant pathogens, reduces organic matter volume, and produces high-quality compost in a short period.

Generally, there are three phases in composting, i.e. mesophilic, thermophilic and maturation. One reason for pathogen contamination in compost could be due to the decomposition phase not reaching the thermophilic stage, where the maximum temperature is obtained, which helps in the decontamination process. Thermophilic composting is a temperature-based method that relies on high temperature to eliminate pathogens. During the active phase of composting, microorganisms generate heat through their metabolic processes, raising the temperature of the compost pile. Maintaining temperatures between 55–65°C (131–149°F) for an extended period is effective in killing many pathogens. Regularly monitoring and managing the compost pile's temperature is essential for successful pathogen removal. According to North American regulatory bodies (United States Environmental Protection Agency and Canadian Council of Ministers of the Environment), pathogen inactivation is expected to occur if all particles of the compost maintain temperatures greater than 55.8°C for at least three days.

Wichuk et al., 2007 described the function of temperature and the length of exposure as the most important factors in the inactivation of pathogens. Other studies have shown that auto sterilization of the composting process induced by relatively high temperatures (60±55°C) caused a significant change in bacterial communities. Temperatures above 55

°C are important to maximize sanitisation. Meanwhile, temperature between 45 °C and 55 °C are required to improve the biodegradation rate and between 35 °C and 40°C to increase microbial diversity. The optimum temperature for the composting process is considered to be approximately 60 °C according to maximizing respiration rate and CO_2 evolution rate. Furthermore, in the thermophilic range, the optimum temperature determines to be 54ºC by studying the effect on oxygen uptake rate, specific growth rate and enzymatic activity of microorganisms.

For instance, in an experimental study on windrow composting, *Escherichia coli* and *faecal Streptococci* populations decreased, respectively, from 2×10^7 to 3.1×10^3 and 10^7 to 1.5×10^3 cells/g, whereas yeasts and filamentous fungi decreased from 4.5×10^6 to 2.6×10^3 cells/g. This decrease was presumably the result of the high temperature (60±65°C) and of the unfavorable conditions established during the thermophilic phase. However, a phase of resurgent growth appeared from the ninth week in all windrows which may have occurred due to recontamination.[12]

Moreover, the growth of pathogens such as *Salmonella typhimurium* can occur in compost material at psychrophilic (<15°C) and mesophilic (15–40°C) temperatures. Studies have shown that the number of *Salmonella* nearly disappeared by the end of the second week of the windrow composting cycle as soon as the temperature increased to 60°C, and they were not detected later in the compost.[13] Another study reveals that when the temperature of the compost reaches 60°C, and moisture levels are maintained, *Salmonella* pathogens were killed within 10 hours.

Wichuk et.al., 2007 cite several studies showing that composting at 60–70°C destroy even the resistant forms of protozoa and helminths.[14] The results of a number of studies support the conclusion that *Ascaris* ova will be reduced to non-detectable levels if composting achieves 55.8°C or more for three days.

Note to be taken:

- *The growth of pathogenic bacteria can result in increased treatment times of composting process in order to reach the appropriate hygiene standards. So, the risk of pathogen growth in compost material, even at psychrophilic and mesophilic temperatures, is reduced when the maturity phase of the compost material is increased.*
- *The risk of pathogen growth or regrowth in compost is reduced if a high temperature (thermophilic range) is kept throughout the whole material even for 3 days.*
- *It's also worth bearing in mind that you don't want your compost to get too hot. Too much heat can destroy the diversity of beneficial bacteria, including bacteria that can combat pathogens.*

Other than heat, some of the other ways pathogens are removed from compost are as follows.[15]

- **Competition for resources:** Beneficial organisms compete with pathogens for resources in a battle which can take place over carbon, nutrients or space. Fortunately, the beneficial organisms are often better at the competition than the pathogens we want to get rid of. For example, in more mature compost, they have a better ability to digest the remains of rotting plants and wood (a characteristic known as saprophytic).

- **Microorganisms attack on pathogens:** Some studies have found that microorganisms that are found in compost attack and consume pathogens. They release enzymes that weaken the cell wall of the pathogen before penetrating and killing it.

- **Antimicrobial and antibacterial properties:** Compost also contains certain compounds that are known to have antimicrobial properties. For example, compost contains lignin, which has antifungal properties, as well as phenols, which has antibacterial properties. In addition, compost also contains humic and fulvic acids, which are known to have antiviral properties. These acids can bind to and inactivate viruses, preventing them from infecting cells and spreading disease.

- **Pasteurization:** Pasteurization involves subjecting compost to moderate temperatures for a specific duration to reduce pathogen levels. This method is typically used for compost that will be used in horticultural applications or where regulatory requirements dictate pathogen reduction. Pasteurization temperatures are typically between 55–70°C (131–158°F), maintained for a shorter duration compared to thermophilic composting. Techniques such as tunnel pasteurization or steam injection can be employed to achieve pathogen reduction. A study revealed that pasteurization at 70°C for 60 minutes is sufficient to achieve a 5 $\log_{10}$ reduction in *Salm. Senftenberg W775* and *Enterococcus spp.* and a 3 $\log_{10}$ reduction in bacteriophage ΦX174 in NaCl, and in fresh and dried cattle manure under laboratory conditions.[16]

- **Compost-vermicomposting system:** Another method for pathogen removal is by combination of composting and vermicomposting. As compost cools down and enters the maturing compost stage, worms will find and enter the heap. A number of studies have suggested that these worms can reduce pathogens. Indeed, a 2011 research article described worms' bodies as 'biofilters' that can purify, disinfect and detoxify solid waste. By combining the two systems—compost and vermicomposting—composting process can be sped up and we get a product that is more stable and consistent (homogenous), has less potential impact on the environment and meets the pathogen reduction requirements. In this method, the red wiggler earthworm or red worm, also known as tiger worms, are added during the composting. These worms feed on vegetable waste and kitchen scraps. They transform waste material into highly fertile manure. Moisture content should be maintained properly as it should not harm the worms. Proper moisture control supports the microbial growth and prevents the pathogen survival caused by excess moisture.[17, 18]

Recommendations for best practices for pathogen-free compost production

Table 6: Optimum conditions to facilitate pathogen free compost

Setting up your compost?	
Location	Choose a spot that is relatively flat, provides adequate drainage, and is away from windows and living areas.
Ingredients	Use a variety of organic materials, including leaves, lawn trimmings, food scraps, and wood chips. For best results, follow the carbon-to-nitrogen ratio of 25:1.
Layering	Layer ingredients in 2–3 inch layers, starting with an inch of carbon-rich materials, then nitrogen-rich materials, and finally top it off with carbon again
Moisture	Keep the pile moist, but not too wet. Use a hose or watering can to add water when necessary.

Composting system design and operation:

- The viability of composting depends on the availability of land to accommodate the composting process, and either manual labour or mechanical equipment to carry out the tasks associated with composting, particularly the turning of windrow piles. However, the aim of designing composting systems should be to facilitate proper aeration and moisture control, allowing for efficient decomposition and pathogen inactivation.
- Implement appropriate turning and mixing techniques to ensure homogeneity and proper heat distribution within the compost pile.
- Consider the use of insulated composting systems or windrows to maintain higher temperatures during the composting process.
- Incorporate features such as leachate collection systems and runoff management to minimize the potential for cross-contamination and environmental impacts.

- Heat distribution depends on the state and composition of the municipal solid waste, whereas heat loss depends on the size and shape of windrow. Accumulation of heat normally occurs in the central zone and is also affected by the size and shape of the windrow.
- A large windrow size should be avoided, as there is a risk of formation of anaerobic zones. A suggested permissible height of the windrow is 1.5 m. Larger pile enables the compost to get hotter. An alternative is to use an insulated hot composting bin.
- Heat loss is proportional to the surface area of the compost mass and heat generation is proportional to volume of the compost mass. Hence, the larger the pile, the greater will be the temperature increase and heat loss will also be diminished.

Feedstock selection and preparation:

- Source feedstocks from reliable and reputable suppliers to minimize the risk of introducing pathogens into the composting process.
- Avoid using feedstocks that are known to be contaminated with high levels of pathogens, such as sewage sludge from unknown sources.
- Implement proper pre-processing techniques, such as shredding or grinding, to enhance the breakdown of feedstocks and facilitate pathogen exposure to composting conditions. Composting may be accelerated by shredding the compostable materials into smaller sizes. However, excessive shredding results in compaction, leading to poor porosity and aeration. The most suitable fraction size for composting is a maximum of 50 mm. To ensure high performance of a composting process, optimum levels of particle size between 3.1–12.7 mm is required.
- Consider blending different feedstocks to optimize nutrient balance and microbial activity, which can contribute to effective pathogen removal.

Segregation of source waste material

Segregation ensures that only high-quality, non-contaminated materials are introduced into the compost pile. This improves the overall quality and safety of the compost product.

- Segregation of source materials before composting plays a crucial role in reducing the presence of pathogens in the final compost. By separating potentially contaminated materials from the composting process, the risk of introducing pathogens into the compost pile is significantly minimized. Here's how segregation helps:
  a. **Eliminating contaminated materials:** Segregation allows for the identification and removal of materials that are known to be contaminated with pathogens. This includes materials like pet waste, meat, dairy products, and non-composted manure, which may contain high levels of pathogens that can persist through the composting process.
  b. **Preventing cross-contamination:** Segregating materials helps prevent cross-contamination between uncontaminated and potentially contaminated materials. By keeping contaminated materials separate, the risk of pathogens spreading to other compostable materials is reduced.
  c. **Targeted treatment:** Segregating certain material allows for specific treatment methods to be applied to potentially contaminated items. For example, animal manure or food waste can undergo separate treatment processes, such as pasteurization or composting at higher temperatures, to ensure pathogen reduction before being reintroduced into the composting system.
  d. Avoid using meat, dairy, fats and oils in compost piles as they may produce pungent odors, attract unwanted pests and slow down the decomposition process. So preferable not to add slaughterhouse waste to MSW waste piles as it requires specific closed systems or in-vessel systems.

Temperature and moisture management:

- Monitor and control compost pile temperatures to ensure the achievement of thermophilic conditions (55–65°C or 131–149°F) necessary for pathogen inactivation. Pathogen inactivation is expected to occur if all particles of compost maintain temperatures greater than 55.8°C for at least three days.
- Regularly measure and adjust moisture levels to maintain optimal moisture content (40–60 per cent) for microbial activity and decomposition while avoiding excessive moisture that can promote pathogen survival. Wastewater or treated water should never be used to sprinkle over the compost pile to maintain the moisture content. Instead, freshwater should always be used.
- Utilize moisture probes or visual inspection techniques to assess moisture content throughout the composting process and make necessary adjustments.

Time-based management:

Maturation and curing:

- Maturation and curing refers to the extended storage of compost after the active composting phase. During this period, the compost undergoes further decomposition and stabilization, allowing time for any remaining pathogens to naturally decline. Maturation periods can range from several weeks to several months, depending on the specific composting process and desired level of pathogen reduction.
- Maturity of compost addresses microbial activity and stability of the product. Less microbial activity indicates better stability. This relationship implies that mature compost should not show phytotoxic properties or nutrient immobilization on its application. Due to variations in the raw materials used in the composting, changes in the C: N ratio need to be monitored rather than considering absolute values. For mature compost, the ratio of final C: N and initial C: N should be less than 0.7524.
- **Storage and aging:** Similar to maturation and curing, storing compost for an extended period can contribute to

pathogen reduction. Proper storage conditions, including adequate aeration and moisture control, facilitate microbial activities and the continuous decomposition of organic matter. The aging process allows time for pathogens to naturally die off, resulting in safer compost. Previous CSE study on quality assessment of compost also recommended that drying the finally matured compost in an open area on a concrete platform for a week reduces the moisture and the microbial load as well.

Aeration and moisture control:

- Maintaining appropriate aeration and moisture levels in the compost pile is crucial for pathogen removal. Adequate aeration ensures the supply of oxygen to the composting microorganisms, promoting their activity and the breakdown of organic matter.
- Oxygen is essential for composting as the organisms involved in the composting process generates energy for their growth and metabolism by the oxidation of carbon compounds. The optimum range of oxygen during various stages of composting is 13–18 per cent.
- Proper moisture control supports microbial growth while preventing excessive moisture that can promote pathogen survival. The optimum moisture content of organic wastes or mixtures of wastes for rapid aerobic thermophillic composting ranges from 40 to 60 per cent (by weight). If the moisture content exceeds 60 per cent, there may be insufficient air space to sustain aerobic decomposition and anaerobic conditions may prevail. With relatively low moisture (40 per cent or less), mobility of micro-organisms may be adversely affected.
- The moisture level should not be more than 20 per cent in ready compost as it promotes the pathogen regrowth in compost piles at storage area. *Salmonellae* regrowth in previously composted waste was found to occur in moisture content of more than 20 per cent and requires a carbon/nitrogen ratio in excess of 15:1.

Composting additives/activators and Amendments (pest control):

- The use of specific additives and amendments can aid in pathogen removal during composting. For example, adding high-carbon materials like wood chips or straw can help in increasing the temperature and enhance microbial activity, facilitating pathogen inactivation.
- Some additives, such as mature compost or microbial inoculants, introduce beneficial microorganisms that can outcompete pathogens and contribute to their reduction. Moreover, the procedure for introducing and preparing organic additives, such as indigenous microorganisms or effective microorganisms, requires minimal expenditure.
- Items such as alfalfa meal, bone meal and blood meal or compost starters are great for adding microbes that help break down material.
- If flies or maggots appear in the pile, add some carbon-rich material or cover the pile with a layer of hay or straw.

Compost turners and mixing techniques:

- Regular turning and mixing of the compost pile promotes aeration, moisture distribution and the homogenization of organic materials. These practices enhance microbial activity and heat distribution, supporting pathogen removal.
- The 24 hour turning frequency has been observed to be optimum for effective pathogen removal during windrow composting.
- Compost turners, including mechanized equipment or manual methods, are used to physically turn the compost pile, ensuring that all materials are exposed to favorable composting conditions.

Monitoring and testing protocols:

- Develop and implement robust monitoring protocols to assess the effectiveness of pathogen removal.
- Conduct regular sampling of compost for pathogen analysis using appropriate techniques, considering

factors such as sample representativeness and sampling frequency.

- Employ reliable and validated testing methods for pathogen detection and quantification, including traditional culture-based methods, molecular techniques or rapid testing technologies.
- Establish clear criteria or thresholds for acceptable pathogen levels in compost based on regulatory guidelines and industry best practices.
- Following are the testing protocols for testing of pathogens,
  - **Faecal coliform:** The faecal coliform in the compost samples can be analyzed by the MPN method according to the protocol given in "Method 1680" of USEPA (2014) and USDA, MLG Appendix 2.05 (2014).[19]
  - ***E. coli:*** The E. coli in the compost samples can be analyzed by MPN method according to the protocols given in APHA 9221 B and 9221 F, (23rd ed., 2017) and USDA, MLG Appendix 2.05 (2014).[20, 21]
  - ***Salmonella:*** The enumeration of *Salmonella spp.* can be carried out by Method 1682: *Salmonella* in sewage sludge (Biosolids) by Modified Semisolid Rappaport-Vassiliadis (MSRV) Medium.[22]

Summary

The production of pathogen-free, high-quality compost is a crucial component of sustainable waste management and agricultural practices. This report highlights the significance of a proper pathogen-free composting system design, emphasizing considerations such as temperature, carbon to nitrogen ratio, aeration, moisture control, compost maturation and turning techniques. Moreover, effective composting systems facilitate optimal decomposition and pathogen inactivation, contributing to the production of safe compost. Additionally, feedstock selection and preparation play a pivotal role in pathogen reduction. Sourcing feedstocks from reliable suppliers and avoiding contaminated materials are essential steps in minimizing pathogen presence. Apart from this, pre-processing techniques, including shredding and grinding, enhance microbial access and pathogen exposure, further contributing to pathogen reduction. By breaking down waste into smaller particles, more particle surfaces with pathogens are exposed to the beneficial microbes, increasing the chances of pathogen reduction. Also, temperature and moisture management are key factors in pathogen reduction. Maintaining thermophilic conditions during composting is vital for pathogen inactivation. Monitoring and controlling compost pile temperatures, along with optimizing moisture levels, ensure favorable conditions for microbial activity and pathogen reduction. Along with this, monitoring and testing protocols are essential for assessing the effectiveness of pathogen reduction.

To effectively reduce or eliminate pathogens in compost, a combination of temperature-based methods, time-based methods, aeration and moisture control, composting additives, and proper turning and mixing techniques should be employed. It is crucial to comply with regulatory standards and provide education and training to composting operators. By adhering to regulations, offering training, and promoting awareness of best practices, we can ensure safe compost production.

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