CHAPTER

Compost feedstocks

4

Authors: Robert Rynk[1], Mary Schwarz[2]

[1]*SUNY Cobleskill, Cobleskill, NY, United States;* [2]*Cornell Waste Management Institute, Cornell University, Ithaca, NY, United States*

Contributors: Tom L. Richard[3], Matthew Cotton[4], Thomas Halbach[5], Stefanie Siebert[6]

[3]*Pennsylvania State University, State College, PA, United States;* [4]*Integrated Waste Management Consulting, Richmond, CA, United States;* [5]*Extension Professor Emeritus, University of Minnesota, Minneapolis, MN, United States;* [6]*European Compost Network, Bochum, Germany*

1. Introduction

Feedstocks are the raw ingredients for composting. They are organic materials, usually solid, and usually in an active state of decomposition. More than any other factor, the feedstocks determine the character of the compost and the temperament of the composting process. Important process and product-related properties of feedstocks include moisture, carbon and nitrogen content, physical characteristics, and level of contamination and value.

Overall, the list of potential ingredients is large and diverse (Table 4.1). Nearly any organic material can be converted to compost. Common feedstocks include manures; leaves, and yard trimmings collected from homes, parks, and other landscapes; food waste from residential and commercial sources (grocery stores, universities, schools, restaurants, hotels, hospitals, outdoor markets, fairs, and festivals and warehouses); biosolids from wastewater treatment (i.e., treated sewage sludge), digestate from anaerobic digesters; food processing residuals; industrial by-products like paper mill sludge; shredded wood; and mixed municipal solid waste (MSW) (Fig. 4.1). Efforts to limit greenhouse gas emissions are diverting increasing amounts of food waste to composters (Frischmann, 2018). This trend is expected to continue as long as methane escapes from landfills and climate change is taken seriously.

Despite the fact that the feedstocks change drastically through the process, they carry through many of their original qualities to the compost, including organic matter, nutrients, minerals, salts, particle size, and contaminants. Feedstocks with relatively high levels of nutrients and salts tend to produce compost with relatively high levels of nutrients and salts. Feedstocks littered with inert contaminants tend

The Composting Handbook. https://doi.org/10.1016/B978-0-323-85602-7.00005-4

Table 4.1 Common and uncommon feedstocks for composting.

Alcohol stillage
Anchovies
Animal mortalities
Apple pomace
Aquatic weeds
Bamboo, stems and leaves
Banana pulp
Biosolids (wastewater sludge)
Blood (from abattoirs)
Bread and breadcrumbs
Brewer's grains
Brush (chips, shredded, etc.)
Butcher wastes (meat, bones, fat)
Cannabis, seized and legal residues
Carcasses from road kill
Cardboard (corrugated, coated, paperboard, etc.)
Cattle manure
Citrus fruit rinds and pulp
Coal ash
Cocoa shells
Coconut coir
Coffee grounds
Compost (recycled)
Contaminated soil (petroleum, munitions, etc.)
Cork
Corn cobs and stover
Cotton gin trash (leaves, stems, etc.)
Cotton mattresses
Crab and lobster shells
Cranberry plant residue
Currency, shredded
Deciduous tree leaves
Diatomaceous earth (w/filter cake)
Pharmaceutical gel caps
Dissolved air flotation (DAF) sludge
Dog food
Drilling mud
Elephant manure

Fats, oils and grease (e.g., from traps)
Filter press cake (apple, olive, etc.)
Fish kills
Fish processing wastes
Flower seed screenings
Fruit, culled and spoiled
Garlic culls and plant residues
Gelatin production waste
Glucose solution
Grain (burnt, spoiled and wasted)
Grape pomace
Grass clippings
Gypsum and dry wall
Hay, spoiled and wasted
Horse manure, stables and racetrack
Ice cream manufacturing waste
Leather
Lees (fruit fermentation sediment)
Lime
Mixed food waste (residential, grocery, school, restaurant, etc.)
Mollusk shells
Newspaper
Night soil (human waste)
Olive processing wastes
Onion culls
Organic textiles and textile residues
Palm oil processing wastes
Paper
Paper mill sludge
Pasta (wet, dry and boxed)
Paunch manure
Peanut shells
Peat moss
Wood chips
Pine needles (and other conifers)
Potato culls
Potato peels

Poultry manure
Rabbit manure
Rice hulls
Salsa processing waste
Sausage casings
Sea urchin
Seaweed
Septage (septic take solids)
Shark carcasses
Sheep manure
Shrimp waste
Silage, spoiled and feed refusals
Spent hops
Straw
Sugarcane bagasse
Sugarcane press mud (filter cake)
Sunflower shells
Swine manure
Tannery wastes (e.g., hides, sludges)
Tare dirt (soil from beets, potatoes)
Tea
Telephone books
Tobacco
Tomato paste processing waste
Tree bark
Trout manure
Vanilla bean residues
Vegetables—culled and spoiled
Vitamin residuals
Walnut shells
Waste beverages, in bulk tankers
Waste beverages, in containers
Water hyacinth
Whey (from cheese and yogurt)
Wood ash
Wood sawdust and shavings
Yard trimmings, mixed
Zoo manure and bedding

FIGURE 4.1

Examples of common and diverse composting feedstocks: (A) mixed yard trimmings, (B) supermarket wastes, (C) dairy cattle manure, (D) horse stable wastes, (E) straw, and (F) food processing waste from tomato products.

to produce compost with more of these contaminants, although processing can improve the result with some organic contaminants. The market value of a compost product depends on the feedstocks from which it was made and a very low level of contamination.

With respect to the process, the feedstocks determine how fast and how far decomposition proceeds, the character of odors generated, the need for moisture, rate of aeration, the temperature rise, and equipment needs. The degradability of a given feedstock dictates how it decomposes within a compost pile, and hence the release of its carbon, nutrients, and odor, and the maintenance of its physical structure. Quickly decomposing feedstocks are more likely to produce odors and rapidly rising temperatures than feedstocks that decompose more slowly. Consequently, the former feedstocks require more aeration and attention than the latter, all other things being equal.

In addition, the feedstocks often dictate what regulations and level of oversight are imposed on the composting operation. Regulations in many jurisdictions name specific materials for which requirements are relaxed and/or specific materials that carry special regulatory provisions. Agricultural by-products are often generated and managed on site tend to be exempt from many regulatory burdens. The regulations tighten with more challenging materials, like food wastes and biosolids. The highest degree of regulation and scrutiny come with feedstocks that have been traditionally viewed as waste materials, like wastewater biosolids and MSW.

Composting can be successful with a single feedstock, such as leaves or bedded livestock manure. However, more often, several different feedstocks are combined, either to improve the process or because multiple feedstocks are readily available. The combination and proportions of feedstocks used in a composting mix are commonly referred to as a "recipe." Sometimes the goal is to compost a given "primary" feedstock, such as a food processing residual, livestock manure, or biosolids. Then, other feedstocks are added to improve the composting characteristics of the primary feedstock. A feedstock added to a recipe to deliberately complement the processing of another feedstock is called an "amendment."

2. Feedstock value

Typically, feedstocks are unwanted by-products, derived from other processes or activities. In the best situations, feedstocks have a positive value for the composter; that is, composters are paid a fee to accept and process feedstocks into compost. Such a processing fee is often called a "tipping" fee or "gate" fee. In other cases, a desired feedstock may need to be purchased in order to produce compost with particular qualities or to improve the composting process. The latter situation usually relates to amendments, like wood chips, when suitable amendments are locally scarce.

Feedstocks that bring a gate fee are tempting. However, such fees can be a mixed blessing. Many feedstocks earn a fee because they are troublesome to handle. Some decompose quickly and quickly turn odorous (e.g., food waste). Others are odorous from the start (e.g., biosolids, fish waste). Some fee-bearing feedstocks need extra processing or carry contamination (e.g., brush, packaged food waste). In addition, just earning a processing fee may shift the composting facility into a more restrictive regulatory category.

On balance, accepting a feedstock for a fee is usually a plus for composters. Indeed, many composters earn more revenue from processing fees than the sale of compost. Whether or not it is practical, profitable and desirable to do so depends on: the fee itself; the costs to obtain the feedstock (e.g., transport); the cost to handle and process the feedstock (e.g., covered storage); and the characteristics of the feedstock including moisture, nitrogen content, physical characteristics like structure and bulk density, level of contamination, and odor risk. The last thing a composter should do is risk the existence of the composting site because of a nuisance-prone feedstock with an enticing gate fee.

3. Feedstock characteristics

The previous chapter discussed the important factors for the composting process. Those factors that can be affected by feedstocks are summarized in Table 4.2. Ideally, the feedstocks should be chosen and mixed in the right proportion to produce characteristics within the ranges listed in Table 4.2. However, it is not necessary, and often not possible, to achieve these values. Composting is a robust and forgiving process. It occurs over a broad range of conditions that can vary quite far from the ideal.

The allowable deviation from the ideal depends on the time available to complete composting, the effect on the compost product, and the consequences when the process strays from the ideal—most prominently the impacts of odors. For rapid composting, or for feedstocks and situations with a high risk of odors, it is prudent to stay close to the ranges in Table 4.2. Moisture content and the carbon-to-nitrogen (C:N) ratio are the feedstock characteristics of greatest concern to the process, and together commonly determine the recipe of the mix. Particle size, bulk density, and pH are also important process-related characteristics that should be considered when selecting feedstocks. The potential for odor should be another prime consideration in selecting feedstocks.

The characteristics of feedstocks not only have an effect on compost process they also have an impact on the finished compost's value. In fact, nearly every attribute of

Table 4.2 Optimal feedstock characteristics for rapid composting.

Condition	Acceptable	Ideal
Moisture content	40%–65%	50%–60% by weight
C:N ratio of combined feedstocks	20:1– 60:1	25–40:1
Feedstock particle size	<5 cm (2 in.)	Variable
Bulk density	<700 kg/m^3 (1200 lbs/yd^3)	400–600 kg/m^3 (700–1000 lbs/yd^3)
pH	5.5–9.0	6.5–8.0

a feedstock contributes to the character of the compost. Organic matter/ash content, macro- and micronutrient levels, soluble salts, and contamination of the feedstock all influence the utility of the resulting compost.

3.1 Moisture

Moisture content is usually a principal factor in developing a composting recipe (see following section). Feedstocks that are dry decompose very slowly and must be either mixed with wet feedstocks or watered. Although the recommended lower limit for moisture content is commonly 40%, a better target for rapid decomposition is 50%. As the moisture content dips below 35%, not only does microbial activity slow down but also dust becomes a concern. Conversely, wet feedstocks compost poorly because excessive moisture increases density and inhibits aeration. The recommended upper limit is typically in the 60%—65% moisture range. The high end of this range works well for feedstocks that are inherently bulky and have particles with a rigid structure. The primary examples are wood by-products. Conversely, feedstocks that are dense or contain a relatively high proportion of soil or other inert components call for a lower level of moisture. Feedstocks that are too wet for composting can be dewatered mechanically (common for some types of livestock manure and biosolids), drained of excess water, and/or dried by the sun and wind. The common remedy for wet feedstocks is to mix them with dry feedstocks.

3.2 C:N ratio

The relative proportions of carbon to nitrogen (C:N ratio) in the feedstocks influences the composting process and the qualities of the compost. The C:N ratio affects the process speed and nitrogen conservation, as the previous chapter explains. During composting the loss of carbon usually far outpaces the loss of nitrogen so the C:N ratio of the compost is substantially less than that of the feedstocks. Still, the starting C:N ratio is a factor in the C:N ratio of the final product. Feedstocks with a high C:N ratio are likely to produce compost with a high C:N ratio, especially if the carbon is bound in resistant compounds, like wood. For general horticultural and agricultural use, it is desirable for the C:N ratio of the compost to be less than 20:1, and preferably below 18:1. Using compost with a C:N ratio greater than 20:1 can lead to N immobilization. On the other hand, compost with a high C:N ratio is good for most mulch and erosion control applications.

The concentration of N in a feedstock largely determines its C:N ratio because N is the lesser quantity. A feedstock with 1% N typically has a C:N ratio half that of a feedstock with 0.5% N. Most raw organic materials have carbon concentrations in the 40% to 50% vicinity. Therefore, feedstocks with low C:N ratios tend to be abundant in N while feedstocks with high C:N ratios can be considered low nitrogen materials.

3.3 Particle size

As described in the previous chapter, particle size has a conflicting influence on the composting process—small particles decompose more quickly but also inhibit aeration. The effect of particle size depends on a material's degradability. Easily degradable materials, like food products, quickly lose their particle integrity within a composting pile. Poorly degradable materials, like wood, hardly decompose regardless of the particle size. Particle size is most relevant to moderately resistant feedstocks such as straw, leaves, vegetation, and paper. Thus, the general recommendation for particle size is fairly broad—0.3 to 5 cm (1/8−2 in.). In general, feedstocks with particles larger than 5 cm (2 in.) benefit from size reduction. Even sawdust particles survive the composting process with little change and become part of the compost. The size of woody particles therefore affects the texture of the compost. Processing operations, such as screening and grinding, offer some control of the compost particle size and texture.

3.4 Bulk density

Bulk density, the mass or weight per unit volume, is a good general index of the quality of a feedstock for composting, with 600 kg/m^3 (1000 lbs/yd^3) being a good target. Bulk density reflects the feedstock's moisture content, porosity, free air space (FAS), and aeration capabilities (see Chapter 3). The bulk density (like porosity and FAS) of a mixture of feedstocks cannot be predicted with accuracy from individual ingredients because particles of different feedstocks intermingle.[1] For instance, the small particles of a dense feedstock fill the voids spaces within a bulky one. Hence, one cannot simply take a weighted average of two feedstocks to calculate the bulk density of their mixture. Still, in sufficient proportions, feedstocks with a low bulk density generally lower the bulk density of a mix and thus improve aeration.

The bulk density of a given feedstock can be highly variable, depending on moisture and its tendency to settle and compact. The compacted material at the bottom of a pile is denser than the material near the top. In addition to the overbearing weight, small particles tend to settle toward the base. The moist material at the center has a higher bulk density than the drier material near the surface. Hence, accurately quantifying the bulk density requires good sampling technique. If the moisture content of a particular feedstock varies considerably, it can be characterized by its dry bulk density (wet bulk density x dry matter content).

3.5 pH

As described earlier, the effect of feedstock pH on the composting process is usually minor, although composting is generally most effective if the mixture of feedstocks

---

[1] Researchers have used statistical methods to predict the FAS of a feedstock mix based on the characteristics of individual feedstocks. See Soares et al. (2013).

has a near-neutral pH. Some quickly degrading feedstocks that are rich in carbohydrates (e.g., potato culls and food waste) can sharply lower the pH of the pile early in the composting cycle. This effect, which can acerbate odors, is preventable with strong aeration. The pH of the starting materials does influence the product. The pH of the compost tends to be close to that of the feedstocks. The final pH may be either slightly higher or slightly lower, depending on the process conditions. For those feedstocks with pH near the extremes, amendments can be added to adjust pH upward or downward. For example, wood ash or lime can be added to raise the pH of acid feedstocks (Wang et al., 2017). Similarly, feedstocks with high pH (e.g., some manures and lime-treated biosolids) can be amended with acidic feedstocks or sulfur products typically used to lower soil pH (Ekinci et al., 2000). More often, however, high pH is managed by adjusting the pH of the resulting composts. Again, intentionally manipulating the pH of feedstocks is rarely necessary.

3.6 Organic matter, volatile solids, and ash

The amount of organic matter in the feedstocks plays a part in how much organic matter is in the compost. Generally speaking, feedstocks with more organic matter yields compost with more organic matter. For example, a compost made from manure usually will be higher in organic matter than one made from leaf and yard waste. This relationship is especially true with poorly degradable feedstocks like wood. Highly degradable feedstocks, like food materials, can defy this generality as they thoroughly decompose to carbon dioxide. Also, how the compost is processed also plays a part. Turned compost generally has less organic matter than static pile compost made with the same ingredients, especially if that compost is on a soil pad where soil can be incorporated into the mix during turning.

Organic matter content is nearly the same as another characteristic called "volatile solids" (VS). The difference is that VS also includes nonorganic compounds that easily vaporize, like ammonia. Usually, one value can be taken as a reasonable approximation of the other. Ash is the reverse of VS (or organic matter). Ash content, in percent, is 100% minus the VS content in percent (or organic matter).

3.7 Nutrients

The nutrient concentrations in the feedstocks determine the nutrients of the compost. The levels of nutrients such as nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), sulfur (S), and zinc (Zn) in the compost product can have an effect on its quality and use. Because nutrients are mostly conserved through the composting process, as carbon is lost, the remaining nutrients are concentrated in the compost. Nitrogen is a possible exception but only if conditions like a low C:N ratio and high pH encourage large losses of N. Minor losses of S, P, and K can also occur but the general relationship holds—the nutrients in the feedstocks determine the nutrient levels in the compost and the concentrations tend to increase from start to finish.

3.8 Soluble salts

Soluble salts are ions of minerals that easily dissolve in water. They are not harmful in themselves. In fact, many salts are essential nutrients for plants and microorganisms (e.g., nitrate). However, high concentrations of salts can damage plants, so it is desirable to limit the concentration in the compost. Salts in compost come from the feedstocks. Hence, it is generally advisable to avoid feedstocks that carry relatively high concentrations of salts. Unfortunately, livestock and poultry manures fall into this category, along with many sources of food residuals. Allowable salt concentrations in the compost depend on the intended use of the compost. Salt concentrations are affected by precipitation and leaching. Composting in the open, without a cover, or at least curing in the open can reduce compost salt level. If salts are high, blending of compost products and mixing with low salt content feedstock dilutes or manages the salt. Specific quantitative recommendations for maximum salt concentrations in feedstocks have not emerged. The common approach is to avoid "salty" feedstocks if necessary and when possible and otherwise control salt levels by blending the compost product or managing its use.

3.9 Odor risk

Feedstocks that have a strong odor or turn rancid quickly require special handling. Odor risk is closely related to degradability. There are two related odor risks. First, odor-prone feedstocks can impose their distinct odors to the composting site when they are delivered. Second, these feedstocks require more aeration and process control to minimize odors during the active composting stage. In locations that are vulnerable to odor complaints, strong-smelling materials such as fish processing waste, food, poultry manure, and biosolids are best avoided or composted inside a building or vessel.

Balch et al. (2019) rate the odour potential of numerous feedstocks. Overall, the feedstocks judged to have the highest odour potentials are those that are wet, quickly degradable (putrescible), and/or rich in N, S, protein or fats. Chapter 12 discusses odor management principles in detail.

4. Feedstock contaminants

Possible contaminants in composting feedstocks include physical contaminants that detract from the appearance and value of the compost, chemicals that might compromise its use, and trace elements (e.g., heavy metals) and biological materials that present health concerns at elevated concentrations.

4.1 Physical contaminants

Physical contaminants are unwanted inert (i.e., inorganic) items that arrive with the feedstocks. Inert contaminants pass through the composting process and become concentrated and more visible in the compost. Common examples include: rocks and metal hardware scraped up with manure; bottles, synthetic fiber, tennis balls, glass, parts from vehicles, and many other items collected in with leaves and yard trimmings; staples in cardboard boxes; labels attached to fruits and vegetables; rubber bands and containers in food waste; and plastics in almost any feedstock (Fig. 4.2).

The most troublesome contaminant is plastic. Plastic is the scourge of nearly all composters. The rise of food waste composting has only worsened composters' contamination woes. Plastic comes in film, foam, hard, and composite forms. It is ubiquitous and difficult to thoroughly separate from compost by mechanical means. Feedstocks that are heavily contaminated with plastic and other inert items are costly to process. The best approach is to replace or separate plastic items at the source. Compostable plastic products and plastic substitutes offer a potential source-based solution but also have their pitfalls (see Section 8.11).

A more recent type of plastic contamination is microplastics. Microplastics are plastic particles less than 5 mm in size. They primarily find their way into compost from feedstocks that contain items that are lined or coated with plastic, including paper beverage cartons, drinking cups, frozen food packages, plastic-lined paper bags, and some paper plates (Brinton et al., 2018). Small plastic particles remain behind after the organic fraction of these items decompose. Microplastics have been found in compost and soils amended with compost. They pose potential concerns to the soil environmental and that of adjacent surface waters (Weithmann et al., 2018; Watteau et al., 2018). At present, there are no regulations or guidelines regarding microplastics in composting or compost. The best prevention is to avoid specific plastic-treated items that carry these contaminants or the associated feedstocks (e.g., food waste, biosolids, MSW, and some digestates). There is evidence

FIGURE 4.2

A variety of physical contaminants removed with screen overs after screening compost. The contaminants arrive with the feedstocks.

Source C. Oshins.

that particular composting practices, such as very high temperatures and/or inoculants, can help degrade microplastics through the composting process (Chen et al., 2020), but the issue is still developing.

4.2 Chemical contaminants

Possible chemical contaminants in composts primarily include pesticide residues and medications. Pesticide residues may accompany hay, straw, greenhouse residues, and other crop residues; grass weeds, leaves, and general yard trimmings; or manure. Antibiotics and other medications pass through the manure when animals are treated for illness. Although not every chemical compound has been studied, research results suggest that most pesticides and medications generally decompose during composting. However, there are a few notable exceptions.

Concerns about contamination of compost with pesticides include the effect of herbicide residues on plants; human exposure from eating crops; children ingesting the compost directly; and general environmental and ecosystem effects. The occurrence, fate, and degradation of pesticides during composting have been widely studied. Investigations of pesticide residues in composting feedstocks and finished compost detected few pesticides and those that were found occurred at low concentrations (Buyuksonmez et al., 1999, 2000; Lemmon and Pylypiw, 1992; Strom, 2000; Vandervoot et al., 1997). A few specific herbicides defy this positive generality. Herbicides known as “pyridine” or “pyrimidine carboxylic acids” can persist in high enough concentrations within compost to damage plants when the compost is used (see Chapter 15).

As much as 75% of the antibiotics consumed by livestock in feed are excreted unchanged. In addition, medications other than antibiotics are also used in the livestock industry. Steroids and other hormones, nonsteroidal anti-inflammatory drugs (NSAIDs), ectoparasitics (fly, tick, and lice medications), and anthelmintics (wormers) are commonly used. In human waste, hormones, tranquilizers and stimulants, analgesics, caffeine and vaccines might occur. When contaminated manure and effluent are used to fertilize agricultural soils, loads of up to kilograms per hectare may be reached. These antibiotics and medications are of concern because they may increase the incidence of antibiotic resistance among a wide variety of pathogenic bacteria as well as having potential deleterious effects on soil bacterial populations. Research examining the fate of antibiotics in composted manure indicates that chlortetracycline, monensin, tylosin, and oxytetracycline are rapidly reduced during the composting process (Arikan, 2007, 2009; Dolliver et al., 2008; Donoho, 1984; Storteboom et al., 2007).

Steroids such as estrogen, estadiol, progesterone, and testosterone (largely excreted in human and animal urine) degrade slowly in manure, soil, and water. Normal wastewater treatment plant conditions do little to degrade these compounds (Khan et al., 2008; Pauwels et al., 2008). Composting and composts rich in microorganisms, including bacteria, actinomycetes, and fungi can degrade or transform these compounds into less toxic substances and/or lock up pollutants within the organic matrix, thereby reducing pollutant bioavailability (Puglisi et al., 2007).

NSAIDs are quickly metabolized in the body and are generally not excreted in the feces. However, vultures in South Asia were poisoned by diclofenac (an NSAID) after scavenging on livestock treated with the drug shortly before death. Composting these carcasses would not only have degraded the diclofenac, but also removed them from access by the vulture. Concern has been raised that the use of antiparasitic agents and anthelmintics in livestock may adversely affect harmless or beneficial organisms, which breed in or feed on dung and play a vital role in the processes in the decay of manure on pastures. There has been little to no research done on the fate of these compounds in composting, but it appears that they do not have much effect on the decomposers in the manure, so composting can occur (McKellar, 1997). Finally, there is concern, about the use of the euthanasia drug, sodium pentobarbital, when composting mortalities. Sodium pentobarbital has been shown to degrade during the composting process so that by the time composting is finished (within six months), very low concentrations of the drug remain (see sidebar Chapter 6).

Other possible chemical contaminants in feedstocks include residues from cleaning and disinfecting products and personal care products. These items might be present in some levels in MSW, septage, and biosolids. Nothing in these categories of chemicals has been found to impair the composting process or compost products. Some composts derived from MSW have contained boron at phytotoxic levels.

At the time of this writing, there is heightened apprehension about a group of widely used industrial compounds known by the acronym PFAS (per- and polyfluoroalkyl substances). PFAS includes the more notorious compounds: Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS). Some of these chemicals have been linked to some health issues in humans. Consequently, they are currently raising questions and spurring changes to drinking water, environmental and consumer product standards. Many industries have phased out the use of the PFOA and PFOS.

The problem for composters is that PFAS have been widely used, over decades, in numerous products, including textiles (e.g., carpets, furniture, and clothing), cookware, food service products (e.g., paper plates), and firefighting foam. They tend to be persistent chemicals and water-soluble. Therefore, residues of PFAS compounds are prevalent in the environment and in wastes, including composting feedstocks. Food waste, biosolids, and paper mill residuals earn the most attention, but small concentrations can even be found in leaves and yard trimmings. In Europe and elsewhere, compost standards include limits on fluorine concentration, partly in response to current PFAS concerns. Such standards may especially affect the development and use of biodegradable food service products.

The present situation, circa 2020, does not require composters to do anything out of the ordinary regarding feedstocks and PFAS, other than remain aware of developments. The situation is fluid. It may never significantly affect composters. For more and updated information about PFAS and composting, monitor the pages of BioCycle Connects (see Beecher and Brown, 2018; Coker, 2000a). Also, the USCC maintains a PFAS web page at (https://www.compostingcouncil.org/page/pfas).

4.3 Trace elements

Trace elements, including heavy metals, are regulated because high concentrations of some elements pose health and/or environmental risks. Prime examples include lead, copper, zinc, arsenic, and cadmium. All naturally occurring materials contain trace elements. Some trace elements are necessary nutrients for plants and humans. With these elements, it is the concentrations that matter, not their presence per se. The concentrations of trace elements in typical composting feedstocks are usually well below the standards established (internationally, the standards differ greatly among countries, see Chapter 15). Wastewater biosolids and MSW are the feedstock most likely to challenge the limits. However, copper or zinc levels also can be high in manure where copper and zinc sulfate footbaths are used, or if copper is provided as a dietary supplement for livestock.

4.4 Biological contaminants

The primary biological "contaminants" of concern are pathogenic organisms that are inherent to the feedstock. Since the composting process effectively destroys animal and plant pathogens, the concern is small. Nevertheless, feedstocks that contain more pathogens merit more attention to temperature management and handling to avoid cross-contamination. For human pathogens, biosolids, MSW, and postconsumer food waste pose the greatest concern. Manure and plant debris carry livestock and plant pathogens and should be handled and composted at thermophilic temperatures. When the compost process is rushed in the primary phase, pathogen regrowth or reestablishment can occur. Another possible biological contaminant is weed seeds. Feedstocks that carry abundant weed seeds should be either avoided or composted at thermophilic temperatures to kill the seeds.

In most jurisdictions, regulations require specific time-temperature regimes for sanitization (e.g., PFRP) when composting biosolids, MSW, or postconsumer food waste (see Box 3.4 in Chapter 3). In some jurisdictions, these sanitization requirements apply to all feedstocks.

5. Biodegradability

The degradability of a given feedstock governs how quickly and completely the feedstock decomposes within a compost pile. Hence, degradability also determines the availability of the feedstock's carbon and the maintenance of its physical structure. In composting, it is the biodegradability that counts because organic compounds are primarily decomposed by biological agents (i.e., microorganisms and enzymes).

Organic materials greatly differ in their speed and extent of decomposition. Compare, for example, a pile of wasted fruit to a pile of green wood chips. The fruit pile promptly decomposes, slumps in a wet puddle, and releases odor while the wood chip pile stands unchanged for months or years. Fig. 3.13 in Chapter 3 presents a hierarchy of biodegradability with various feedstocks included.

Ignoring the effects of moisture and particle size, the biodegradability of a feedstock depends on its chemical make-up. Sugars and starches decompose quickly because of their simple molecular structure. Fewer enzymes and fewer steps are involved in their decomposition. It takes longer to disassemble compounds of cellulose and hemicellulose, which are chains of simple sugars. Lignins are large and complex organic molecules that defy decomposition (Box 4.1). It follows that feedstocks dominated by sugars and starches decompose quickly while those with abundant lignin hardly decompose at all. The concentration of lignin is a fairly reliable predictor of how thoroughly a feedstock will decompose via composting. Eq. (4.1) is one formula for estimating biodegradation based on lignin content (Richard, 1996, after Chandler et al., 1980).

$$\text{Biodegradable fraction (\% of volatile solids)} = 0.83 - (0.028 \times \text{lignin\% of volatile solids}) \tag{4.1}$$

Box 4.1 The effect of lignin on biodegradability

Author: Tom L. Richard

Plant cell walls are composed of four important constituents: cellulose, hemicelluloses, pectins, and lignin. Lignin is particularly difficult to biodegrade and reduces the bioavailability of the other cell wall constituents. Knowing a bit about each of these constituents is helpful in understanding the vastly different rates at which different plant materials decompose. Cellulose is made of long chains of glucose molecules, linked one to another. The simplicity of cellulose's structure, using repeated identical bonds, means that only a small number of enzymes are required to degrade this material. Hemicelluloses and pectins are branched polymers of several sugar monomers including xylose, arabinose, galactose, mannose, glucose, and acidic sugars. Hemicelluloses and pectins surround and link cellulose, enhancing the strength and flexibility of the cell wall. Hemicelluloses can also cross-link with lignin, creating a complex web of bonds that provides structural strength to the plant, but also inhibits microbial degradation.

Lignin is a complex polymer of phenylpropane units, which are cross-linked to each other with a variety of chemical bonds. This complexity has thus far proven as resistant to detailed chemical characterization as it is to microbial degradation. Nonetheless, some organisms, particularly fungi, have developed the necessary enzymes to break lignin apart. Actinobacteria (aka actinomycetes) can also decompose lignin, but typically degrade less than 20% of the total lignin present. Lignin degradation is primarily an aerobic process, and in an anaerobic environment, lignin can persist for very long periods.

Because lignin is the most resistant component of the plant cell wall, it largely determines the biodegradability of a given type of plant material. With higher proportions of lignin, less of the total carbon is available to microorganisms ("bioavailable"). The effect of lignin on the bioavailability of other cell wall components is thought to be largely a physical restriction, with lignin molecules either reducing the surface area available for enzymes to bind and degrade other components of the cell wall or sequestering those enzymes in an inactive form.

Although significant lignin degradation is possible during aerobic composting, a number of factors are likely to affect the decomposition rate. Conditions that favor the growth of fungi, including adequate nitrogen, moisture, and temperature, all appear to be important in encouraging lignin decomposition, as does the composition of the plant material itself. Lignin is present in all plants, but it is especially abundant in trees and other woody species. Without lignin, our wooden houses would crumble to the ground.

Adapted from the Science and Engineering section of Cornell Waste Management Institute website, http://compost.css.cornell.edu/calc/lignin.html (Richard, 1996).

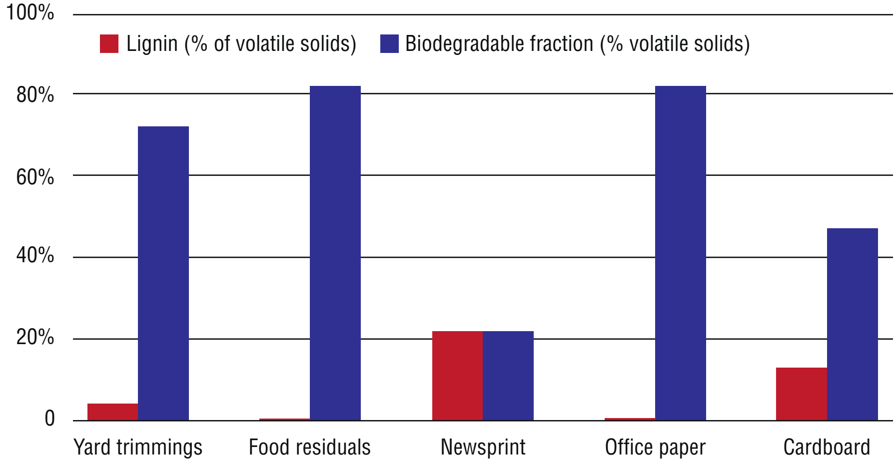


FIGURE 4.3

Estimated degradability of selected feedstocks. Lignin is expressed in percent of volatile solids concentration. Biodegradable fraction is the percentage of dry volatile solids.

Based on data presented by Tchobanoglous et al. (1993).

Fig. 4.3 provides examples of the predicted biodegradability of selected feedstocks based on their lignin content. Degradability can also be tested in the laboratory, or on a pilot scale, if desired, by monitoring carbon dioxide evolution and/or loss of mass over time (Mason, 2009).

A measure of biodegradability can be applied to a feedstock's total carbon in order to estimate its "available" carbon. This approach has been proposed by several researchers including Kayhanian and Tchobanoglous (1992) and Puyuelo et al. (2011). It would be useful for assessing things like oxygen demand, heat generation, and effective C:N ratio. It is somewhat remarkable that using an "available C:N ratio" has not taken hold as common practice, although the recommended C:N benchmarks would also need to be revisited. Presently, judging the bioavailability of carbon in a feedstock mix is left to the experience and intuition of the operator, and remains part of the art of composting.

6. Combining feedstocks—amendments and recipes

In few cases does a given feedstock, in its available condition, possess all the characteristics required for efficient composting. Therefore, it is often necessary to blend several ingredients, in suitable proportions, to achieve a mix with the desired overall characteristics (Fig. 4.4). The mixture of ingredients, and their relative proportions,

FIGURE 4.4

Combining feedstocks for better composting.

is referred to as a *recipe*. A common recipe involving food waste is typically dominated by yard trimmings or/and wood chips. For farms, a composting recipe is often a blend of manure and bedding materials, and possibly crop residues. Sometimes waste products from nearby lumber operations, such as untreated sawdust or bark, are used.

In many cases, composters deal with a primary feedstock, like food, manure, or biosolids. Other feedstocks are then added, either to improve composting of the primary ingredient or simply because they are available for composting.

Ingredients that are deliberately added to a recipe to improve the composting characteristics of a primary feedstock are referred to as amendments, bulking agents, or carbon sources. An amendment is added to adjust any characteristic of the mix, including moisture content, texture, bulk density, or C:N ratio. A bulking agent improves the physical characteristics so that the feedstocks have sufficient pore space and structure for aeration; that is, they stand in a pile without slumping or collapsing. Carbon sources are added to raise the C:N ratio. The three terms are often used interchangeably because common amendments, like wood chips and straw, also add bulk and carbon. “Amendment” is the more general term and is used in this handbook to describe any ingredient added to improve the qualities of a primary feedstock.

In many cases, the primary feedstock to be composted is wet and high in nitrogen, like manure or biosolids. Therefore, dry bulky amendments with a high C:N ratio are often in great demand. Since amendments must often be obtained from outside sources, cost and availability are important factors. For composting to remain economical, the amendments must be inexpensive. Fortunately, many free or inexpensive materials are suitable and available for composting.

6.1 Approaches to developing recipes

A composting recipe is like a cooking recipe. It prescribes the ingredients and their proportions for successfully making the desired product at an acceptable cost. As in cooking, the recipe affects both the process and the product.

A composting recipe can result from any of the following strategies:

- Look and feel—relying on senses to combine feedstocks in a way that produces a mix that looks and feels right for composting. The *feel* typically relates to the moisture level while the *look* may simply answer the question, "Does the pile stand up well on its own?" For instance, more manure or water is added if the mix feels dry. Dry amendments are added until the mix stands in a pile without slumping. This approach to recipe making requires experience and good composting instincts.
- Trial and error—a common approach that is typically partnered with the look and feel strategy. Again, this tactic requires some experience and understanding the composting process. There is the risk that a trial that results in error will cause odor or product quality problems. The key to success is maintaining an awareness of the moisture content, C and N balance, and the other aeration characteristics of the feedstock mix.
- Tried and true—learning from and copying successful recipes from other composters. Some recipes have even been "standardized." For example, a standard recipe for composting biosolids by the aerated static pile method is mixing three volumes of wood chips to one volume of biosolids. The common backyard recipe of three volumes of "browns" to one volume of "greens" is generally sound advice. In this vernacular, the "browns" are low-nitrogen feedstocks, which tend to be dry and often brownish in color. The greens are high nitrogen feedstocks, which tend to be moist and typified by green vegetation. Although brown in color, manure is very "green" by the definition used here. The browns to greens volume ratio of 3:1 usually leads to a safe and workable recipe in large scale composting and the backyard. However, it can result in an unnecessarily costly mix if brown amendments must be purchased.
- Target bulk density—mixing feedstocks to yield a desired bulk density. Because bulk density is a good general index for the physical and moisture character of feedstocks, it is also a reasonable criterion for combining feedstocks. Bulk density cannot be accurately predicted from the densities and proportions of individual feedstocks, so finding the proportions to achieve the target is a trial-and-error exercise. Once the feedstocks mixed, the bulk density easily can be measured directly in the field (Box 4.2). As noted earlier, a good bulk density target falls in the range of 400–600 kg/m^3 (about 700–1000 lbs/yd^3).
- Mathematically balancing moisture—calculations based on only the moisture content of individual feedstocks. With many feedstocks, moisture is the pivotal factor in successful composting. In such cases, it is often sufficient to determine recipes based on the moisture contents of the individual feedstocks. This task can be done mathematically, and easily, using the formulas presented in Table 4.3.

Box 4.2 Procedure for field measurement of Bulk Density and Free Air Space (FAS)

The following procedures for field testing of bulk density and free-airspace (FAS) are recommended by the Composting Research and Education Foundation (CREF) and used in the CREF's Compost Operators Training Course (Oshins, 2019). The bulk density test is completed first and is used as the basis for determining FAS.

Bulk Density Bulk density is calculated by dividing the mass or weight of a collection of particulate material by the volume that the collection occupies. It can be determined by filling a container of known volume and weight with the material to be tested and then weighing the filled container. The bulk density equals the filled container weight minus the empty container weight divided by the container volume.

An inconvenient feature of bulk density is that it is inconsistent. It changes over time as particles settle, lose or gain moisture. It also changes a great deal within the cross section of a pile, so getting a good composite sample is important.

Furthermore, when sampling a pile of material, the inherent density is disturbed. The sample tends to be less dense than the material in its pile. Therefore, some standard repeatable means of compaction is necessary to obtain a consistently representative result. A simple and commonly used procedure for determining bulk density on-site is described below.

1. Tools needed
   - A garden shovel,
   - A 20-liter or 5-gallon bucket or similar standard container, and,
   - A scale able to weigh at least 25 kgs or 50 lbs (e.g., a luggage scale).
2. Confirm and record the volume of the bucket. If necessary, place a mark on the bucket wall at the location that corresponds to 20 liters or 5 gallons. A simple way to find this location is to place the bucket on the scale and add water until the scale reads 20 kg plus the bucket weight or 42 lbs plus the bucket weight. Otherwise, you can pour in four 5-liter containers of water or five 1-gallon jugs.
3. Using the garden shovel obtain representative samples from different locations of the pile. Add the samples to the bucket until the bucket is about *one-third* full (Figure 4.5A). Sample the pile from top to bottom and from the surface to the core (review the sampling tips in Chapter 14).

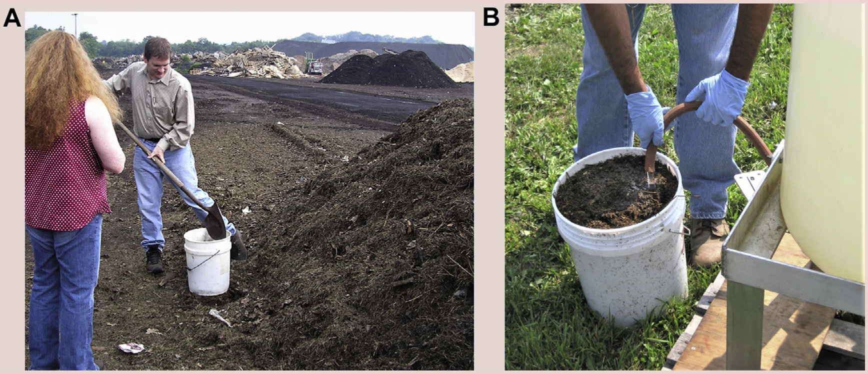


FIGURE 4.5

Field measurement of bulk density (A) and free air space (FAS) (B) using a 5-gallon pail, a shovel, a luggage scale, and water.

Box 4.2 Procedure for field measurement of Bulk Density and Free Air Space (FAS)—cont'd

4. Lift the bucket to so the base is about 15 cm (6 inches) above the ground and drop the bucket onto a firm flat surface. Repeat this procedure for a total of 10 drops.
5. Add additional representative samples to the bucket until it is about *two-thirds* full.
6. Again lift the bucket to 15 cm (6 inches) and drop it to the ground 10 times.
7. Fill the bucket with additional samples to the fill line (e.g., 20-liter or 5-gallon mark).
8. Once again, drop the bucket to the ground 10 times from a height of 15 cm (6 inches).
9. Add more material to the bucket to the 20-liter or 5-gallon mark and weigh bucket and its contents.

Using this procedure, the estimated bulk density is:

$$\text{Bulk Density} = \frac{\text{Filled container weight} - \text{Empty Container Weight}}{\text{Container Volume}} \tag{4.2}$$

Eq. (4.2) gives an answer in kgs per liter or lbs per gallon. The bulk density in more useful units can be calculated directly using Eqs. (4.3) and (4.4). (There are fifty 20-liter buckets in a cubic meter and forty 5-gallon buckets in a cubic yard).

$$\text{Bulk Density}\left(\text{kg/m}^3\right) = \text{kgs/liter from Eq. } 4.2 \times 50 \tag{4.3}$$

$$\text{Bulk Density}\left(\text{lbs/yd}^3\right) = \text{lbs/gallon from Eq. } 4.2 \times 40 \tag{4.4}$$

Free Air Space FAS is a measure of the amount of open space within the material through which oxygen is provided for aerobic bacteria to do their work. It is the ratio of gas-filled volume to total sample volume. It can be measured in the field in much the same way that bulk density is measured. After following steps 1 − 9 above for measuring bulk density, water is added to the bucket to displace the gas-filled void-space between particles. The weight of water added, and its corresponding volume, determines the FAS.

10. Follow steps 1 − 9 above for bulk density.
11. Add water to the filled bucket dually to allow the air bubbles to percolate to the surface. Continue just until the water covers the surface of the material in the bucket (Figure 4.5B). Weigh the bucket again.
12. The difference between the weights of the bucket before and after adding water equals the weight of water added to it.

    Weight of water added = Weight of bucket after adding water − weight of bucket before
13. Volume of water added is the volume of the pore space displaced. It is equal to the weight of water added divided by the density of water. In the case of kilograms and liters, the weight and volume of water are numerically equivalent.

$$\text{Volume of gas-filled pore space (liters)} = \text{Weight of water added (kg)}/\ 1\ \text{kg/L} \tag{4.5}$$

$$\text{Volume of gas-filled pore space (gallons)} = \text{Weight of water added (lbs)}/\ 8.34\ \text{lbs/gal} \tag{4.6}$$

The estimated FAS is the volume of the gas-filled pore space divided by the volume of the contents in the bucket (e.g., 20 liters or 5 gallons). Multiplying by 100 expresses the answer in its common percentage form. of the water added to fill all of the air spaces, divided by the weight of water that would fill the volume of the bucket used. For example, 40 lbs of water will fill a 5-gallon bucket. The resulting number is the percentage of free air space in the sample.

$$\text{FAS}(\%) = 100\% \times \frac{\text{Volume of gas-filled pore space}}{\text{Volume of bucket contents}} \tag{4.7}$$

- Mathematically balancing moisture and C:N ratio—calculating feedstock mixes based on chemical analysis of individual feedstocks. Moisture content and C:N ratio have been the main variables customarily used to develop composting recipes. A recipe for multiple feedstocks can be worked out mathematically, if the moisture, carbon and nitrogen contents of the individual ingredients are known. Table 4.3 presents the related formulas, and Section 6.3 explains the procedures. Computer spreadsheet and dedicated recipe-building programs make the calculations tolerable for even math-phobic composters. By this method, a well-balanced recipe can be developed on paper, and without the cost and effort of trial and error. Because it includes several key factors, this method of recipe development is preferred in situations where process control and speed are important. Thus, it is discussed in more detail in the following sections.

6.2 The prominence of moisture and C:N ratio

Moisture and C:N ratio are two primary characteristics commonly used to determine composting recipes. In part, these characteristics are emphasized because they are measurable and mathematically predictable. However, they are also key factors in the composting process. If the moisture content and C:N ratio are within the recommended ranges, composting will likely go well.

As Table 4.2 indicates, when compost feedstocks are combined, the resulting mixture ideally should fall in a moderate moisture range (50%—65%) and possess a ratio of carbon to nitrogen in the vicinity of 25:1 to 40:1. One can visualize a feedstock's character by plotting these properties on a chart such as Fig. 4.6. The center of the chart represents an excellent balance. The surrounding quadrants delineate conditions for which a feedstock is either too wet, too dry, nitrogen poor, and/or overabundant in nitrogen. Again, it is the nitrogen content of a feedstock that primarily determines its C:N ratio.

Fig. 4.7 maps typical moisture contents and C:N ratios for selected example feedstocks. For example, livestock and poultry manures exhibit the full range of moisture contents but in most cases, manure is wet and high in nitrogen. Livestock bedding and poultry litter materials (e.g., wood shavings) bring down the moisture content and raise the C:N ratio. Assorted feedstocks that come from the landscape or gardens are likely to be balanced if they are well blended. Individually, green materials (e.g., grass clippings, fresh vegetation) tend to be moist and moderately high in nitrogen while brown materials (e.g., autumn leaves, hay/straw, wood trimmings) are usually dry and lack nitrogen. Feedstocks from the food stream are diverse but those most commonly composted (e.g., market produce, kitchen scraps) tend to be very wet and nitrogen-rich. It is vital to understand that specific materials with each type of feedstock tagged in Fig. 4.7 vary greatly and can differ from the positions in the figure.

Charts like these can help a composter visualize how a particular feedstock can be amended or altered to improve its composting performance; that is, move it

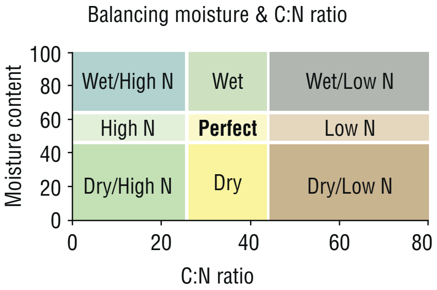
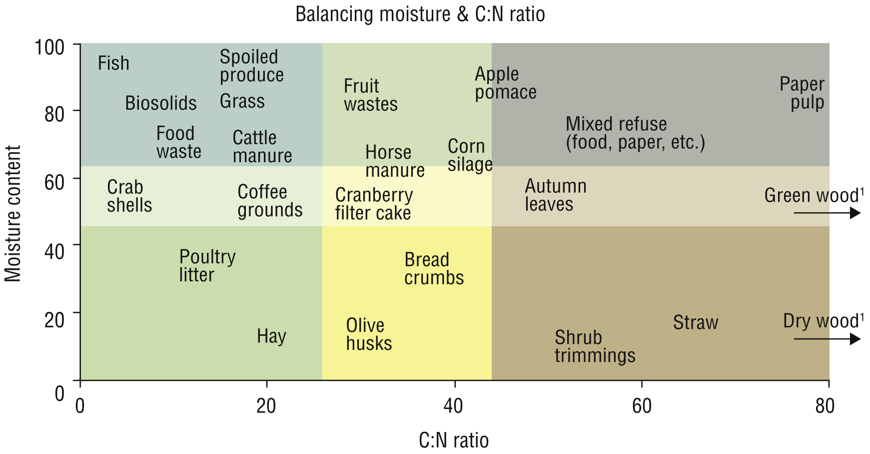


FIGURE 4.6

Generic feedstock moisture and C:N ratio map.



1. The C:N ratio of wood is "off-the-chart." ranging from 250 to over 500

FIGURE 4.7

Typical moisture and C:N ratio positions for selected food feedstocks.

toward the center of the chart. Appendix B lists typical values for moisture, C:N ratio and other characteristics of numerous feedstocks common to composting. It is important to recognize that the C:N ratio and, especially, the moisture content of a specific material can vary greatly depending on its source, management and handling. A laboratory analysis of specific candidate feedstocks from the actual sources is recommended.

6.3 Recipe math

This section outlines the mathematical procedure for developing a composting feedstock recipe based on moisture content and C:N ratio (total C and N). To some readers, the formulas and procedure may be daunting, especially readers without algebra experience. Fortunately, there are ways to follow this recipe-making option without doing the math. Numerous computer spreadsheets and recipe "calculators" are available, either free of charge or for a small fee. An internet search will reveal numerous alternatives. Many of these recipe programs include an embedded inventory of potential feedstocks and an estimate of their C, N, and moisture contents. Some programs go a little further and also consider feedstock costs (Calisti et al., 2020). Appendix C includes a link to the recipe calculator used by CREF in its composting operator training program.

Mathematically developing a composting recipe is a balancing act because both the C:N ratio and the moisture content need to be within acceptable ranges. Usually, one of these attributes takes priority, and an appropriate recipe is determined. Then, if necessary, the proportions are adjusted to bring the second attribute in line without excessively changing the first. Sometimes an acceptable balance cannot be achieved, and a different set of ingredients must be considered.

With wet feedstocks, the moisture content is particularly critical because high moisture content leads to anaerobic conditions, odors, and slow decomposition. The consequences of a poor C:N ratio are less damaging. It is usually better to develop an initial composting recipe based on moisture content and then adjust it, if necessary, to achieve an acceptable C:N ratio.

When working with primarily dry feedstocks, feedstocks can be first proportioned on the basis of C:N ratio. If necessary, water can be added as needed. In this case, the weight of water needed to achieve a target moisture content can be calculated using Eq. (4.8), recognizing that water has a moisture content of 100%. Eq. (4.9) calculates the corresponding volume of water by dividing the required weight by the density of water, about 1 kg per liter or 8.3 lbs per US gallon.

$$\text{Weight of water needed} = \frac{(\text{fw} \times \text{M}) - (\text{fw} \times \text{mf})}{(100 - \text{M})} \tag{4.8}$$

fw is the feedstock weight.
mf is the feedstock moisture content in percent.
M is the target moisture content in percent.

$$\text{Volume of water needed} = \text{Weight of water/Density of water} \tag{4.9}$$

The formulas for calculating a composting recipe are given in Table 4.3. For each ingredient, the moisture content, the concentration of nitrogen and either the carbon concentration or the C:N ratio must be known. If it is necessary to convert from weight to volume or vice versa, the bulk density of the feedstock is also required. Note that carbon and nitrogen concentrations are expressed and calculated on a dry weight basis.

If the literature or test results do not report the carbon concentration but the percentage of organic matter or ash is known, the carbon content can be roughly estimated by the following equation.

$$\%\ \text{Carbon} = \frac{\%\ \text{Organic matter}}{1.8} = \frac{100 - \%\ \text{Ash}}{1.8} \tag{4.10}$$

Eq. (4.10) was proposed in the 1951 by researchers in New Zealand (Golueke, 1972) and it remains valid. It assumes that carbon comprises slightly more than half (56%) of organic matter by weight (i.e., what is not ash). The factor in the denominator (i.e., 1.8) is an average based on many measurements. In individual samples, this factor has since been determined to be as low as 1.6 and as high as 2.2.

Table 4.3 Recipe Math—formulas for calculating composting recipes based on moisture content and C:N ratio.

Formulas for an individual ingredient

Moisture content = % Moisture content/100
Weight of water = total weight × moisture content
Dry weight = total weight – weight of water
= total weight × (1 – moisture content) = total weight × solids content
Nitrogen content = dry weight × (%N /100)
%carbon = %N × C : N ratio
Carbon content = dry weight × (%C/100)
= N content × C : N ratio

General formulas for a mix of materials

$$\text{Moisture content} = \frac{\text{weight of water in feedstock a} + \text{water in b} + \text{water in c} + \ldots}{\text{total weight of all feedstocks}} = \frac{(a \times m_a) + (b \times m_b) + (c \times m_c) + \ldots}{a + b + c} \qquad \text{(Eq. 4.11)}$$

$$\text{C : N ratio} = \frac{\text{weight od C in feedstock a} + \text{weight of C in b} + \text{weight of C in c} + \ldots}{\text{weight of N in a} + \text{weight of N in b} + \text{weight of N in c} + \ldots}$$

$$= \frac{[\%C_a \times a \times (1 - m_a)] + [\%C_b \times b \times (1 - m_b)] + [\%C_c \times c \times (1 - m_c)] + \ldots}{[\%N_a \times a \times (1 - m_a)] + [\%N_b \times b \times (1 - m_b)] + [\%N_c \times ac \times (1 - m_c)]} \qquad \text{(Eq. 4.12)}$$

where: a = total weight of feedstock a
b = total weight of feedstock b
c = total weight of feedstock c
m_a, m_b, m_c, … = moisture content of feedstocks a, b, c, …
%N_a, N_b, N_c, = % nitrogen of feedstocks a, b, c, … (% of dry weight)
%C_a, C_b, C_c, … = % carbon of feedstocks a, b, c, … (% of dry weight)

Shortcut formulas for only two feedstocks (for example, leaves plus grass clippings)

Required amount of feedstock a per kg (or lb) of feedstock b, based on the desired *moisture content* $a = \frac{m_b - M}{M - m_a}$ (Eq. 4.13)

Then check the C:N ratio using the general formula.

Required amount of feedstock a per kg (or lb) of feedstock b, based on the desired C:N ratio $a = \frac{\%N_b}{\%N_a} \times \frac{(R - R_b)}{(R_a - R)} \times \frac{(1 - m_b)}{(1 - m_a)}$ (Eq. 4.14)

Then check the moisture content using the general formula.

where: a = kgs (or lbs) of feedstock a per kg (or lb) of feedstock b
M = desired mix moisture content
m_a = moisture content of feedstock a (for example, amendment)
m_b = moisture content of feedstock b (for example, manure)
R = desired C:N ratio of the mix
R_a = C:N ratio of feedstock a
R_b = C:N ratio of feedstock b

The word "weight" is used to represent both mass and weight units. It is technically incorrect but pragmatic, as long as practitioners remain on a given planet. Also, the formulas for C, N and C:N ratio are for total *C and N on a dry weight basis (not* available *C and N).*

To develop a recipe mathematically, it is necessary to assume the *relative* proportions of the feedstocks being considered. If there is a primary feedstock, it is best to assume that it has a unit of 1 (e.g., 1 ton, 1 metric ton, 1 cubic yard, 1 cubic meter). The proportions of the other ingredients are relative to that ingredient. It is easiest to work in weight or mass units and then convert the final weight proportions to volume (volume = weight or mass ÷ bulk density). Making the calculations with volume-based proportions is extra work, although easily done by a computer.

The sample calculations in Example 4.1 describe a procedure for calculating the recipe proportions, moisture content, and C:N ratio. With only two ingredients, such

Example 4.1 Sample calculations for composting recipe based on moisture content and C:N ratio

On a weekly basis, a farm composter currently handles 20 cubic meters of separated solids from dairy manure and mixes it with eight cubic meters of horse manure. The composter has been offered organic waste from the local market. On average, every week the market generates about five cubic meters of organic waste, which is mostly food with some paper products. The composter plans to add more horse manure to accommodate the moist market waste.

The question is: How much more horse manure should the composter add to maintain a reasonable recipe? As a start, the composter assumes that increasing the horse manure to 10 cubic yards might suffice. The average feedstocks' analysis is listed below.

Feedstocks	Moisture (% wet wt)	Nitrogen (% dry wt)	Carbon (% dry wt)	C:N ratio	Bulk density kg/m^3 (lb/yd^3)
Dairy manure solids (DMSs)	70	1	55	55	550 (927)
Horse manure (HM)	50	1.5	48	32	770 (1289)
Market organics (MO)	78	2.8	52	19	800 (1348)

Given the above analysis and the assumed weekly volumes, the amount of each feedstock available in terms of wet weight, dry weight and water weight are listed below. "Wet weight" is the actual weight (or mass) of the feedstock. "Water weight" is the amount of water in the feedstock. "Dry weight" is the weight (or mass) of everything except the water.

Feedstocks	Weekly volume	Wet weight[a]	Water weight[b]	Dry weight[c]
DMS	20 m^3	11,000 kg	7700 kg	3300 kg
	26.2 yd^3	24,287 lb	17,004 lb	7286 lb
HM	10 m^3	7700 kg	4235 kg	3465 kg
	13.1 yd^3	17,004 lb	9667 lb	7652 lb
MO	5 m^3	4150 kg	3120 kg	880 kg
	6.6 yd^3	9170 lb	6887 lb	1942 lb
Totals	33 m^3	22,700 kg	15,055 kg	7645 kg
	43.3 yd^3	50,121 lb	33,240 lb	16,880 lb

[a] *Wet weight = Volume × Bulk density.*
[b] *Water weight = Wet weight × Moisture content.*
[c] *Dry weight = Wet weight − water weight.*

Step 1: Determine the combined moisture of the feedstocks:
From Table 4.3, the formula for moisture content is:

$$\text{Moisture content} = \frac{\text{weight of water in ingredient a} + \text{water in b} + \text{water in c} + \ldots}{\text{Total weight of all ingredient}}$$

$$\text{In kilograms: M} = \frac{7700 + 4235 + 3120}{22,700} = \frac{15,055\ \text{kg}}{22,700\ \text{kg}} = 0.663 = 66.3\%$$

$$\text{In pounds: M} = \frac{17004 + 9667 + 6887}{50,121} = \frac{33,240\ \text{lb}}{50,121\ \text{lb}} = 0.663 = 66.3\%$$

The resulting moisture content, 66% is slightly higher than desired.
Step 2: Check the resulting C:N ratio:
From Table 4.3, the formula for C:N ratio is:

$$\text{C:N ratio} = \frac{\text{weight of C in ingredient a} + \text{weight of C in b} + \text{weight of C in c} + \ldots}{\text{weight of N in a} + \text{weight of N in b} + \text{weight of N in c} + \ldots}$$

The weight of each nutrient is calculated by multiplying the dry weight of the feedstock by its corresponding nutrient content which is demonstrated in the following table.

Feedstocks	Dry weight[a]	Carbon (C) content[a]	Carbon weight[b]	Nitrogen (N) content[a]	Nitrogen weight[b]
DMS	3300 kg	0.55	1815 kg	0.01	33 kg
	7286 lb		4007 lb		73 lb
HM	3465 kg	0.48	1663 kg	0.015	52 kg
	7652 lb		3673 lb		115 lb
MO	880 kg	0.52	458 kg	0.028	25 kg
	1942 lb		1010 lb		54 lb
Totals	7645 kg		3936 kg		110 kg
	16,880 lb		8690 lb		242 lb

[a] *Carbon content = %Carbon ÷ 100%; Nitrogen content = %Nitrogen ÷ 100%.*
[b] *Nutrient weight = Dry weight x Nutrient content.*

Filling in the values from the above table into the formula:

$$\text{In kilograms : C:N} = \frac{1815 + 1663 + 458}{33 + 52 + 25} = \frac{3936\ \text{kg C}}{110\ \text{kg N}} = 35.8 = 36{:}1\ \text{C:N}$$

$$\text{In pounds : C:N} = \frac{4007 + 3673 + 1010}{73 + 115 + 54} = \frac{8689\ \text{lb C}}{242\ \text{lb N}} = 35.9 = 36{:}1\ \text{C:N}$$

The resulting C:N ratio, 36:1, is excellent. The addition of the market waste will lower the overall C:N ratio and improve it relative to the current recipe using only dairy manure solids and horse manure.

Continued

Example 4.1 Sample calculations for composting recipe based on moisture content and C:N ratio—cont’d

Conclusion The composter would be wise to use more horse manure (the drier feedstock) to bring down the moisture content below 65%. Doing so does not harm the overall C:N ratio because the horse manure has a good C:N ratio in itself, 32:1. Repeating these calculations assuming a weekly horse manure volume of 14 cubic meters (18.3 cubic yards) yields a combined moisture of 65% and content and C:N ratio of 35:1.

All of these calculations are made quickly and easily by a computer spreadsheet program. The following image depicts a spreadsheet layout for this example problem. After inputting the data, a composter only has to try different amounts in the cells of the “Volume” column (orange background) to ascertain the resulting moisture contents and C:N ratios (yellow background) for various combinations of the feedstocks.

Feedstock	**Volume (m^3)**	**Bulk density (kg/m^3)**	**Wet wt. (kg)**	**Moisture content (%/100)**	**Water wt. (kg)**	**Dry wt. (kg)**	**C (% dry wt.)**	**N (% dry wt.)**	**C:N Ratio**	**Wt. of C (kg)**	**Wt. of N (kg)**
DMS	20	550	11,000	0.7	7700	3300	55	1	55	1815	33
HM	10	770	7700	0.55	4235	3465	48	1.5	32	1663	52
MO	5	800	4000	0.78	3120	880	52	2.8	19	458	25
Total and results	35		22,700	66.3%	15,055	7645			36	3936	110

Feedstock	**Volume (yd^3)**	**Bulk density (lb/yd^3)**	**Wet wt. (lb)**	**Moisture content (%/100)**	**Water wt. (lb)**	**Dry wt. (lb)**	**C (% dry wt.)**	**N (% dry wt.)**	**C:N Ratio**	**Wt. of C (lb)**	**Wt. of N (lb)**
DMS	26.2	927	24,287	0.7	17,001	7286	55	1	55	4007	73
HM	13.1	1298	17,004	0.55	9352	7652	48	1.5	32	3673	115
MO	6.55	1348	8829	0.78	6887	1942	52	2.8	19	1010	54
Total and results	46		50,121	66.3%	33,240	16,880			36	8690	242

as manure plus an amendment, the amendment proportion can be calculated directly from the desired moisture content or the desired C:N ratio, as shown in the example. However, if three or more ingredients are used, the recipes must be calculated by trial and error using the general formulas in Table 4.3. In this case, the proportions of the ingredients are first assumed and then the corresponding C:N ratio and moisture content are calculated. If either the C:N ratio or moisture content is unacceptable, proportions are adjusted and calculations are repeated until an acceptable C:N ratio and moisture content are obtained. Appendix D is a presentation-based tutorial for calculating composting recipes, including additional examples.

A computer spreadsheet program is tailor-made for repetitive calculations of this type. Once the characteristics of the candidate ingredients are entered into the spreadsheet, the relative proportions are easily altered to find the best recipe.

7. Determining feedstock characteristics

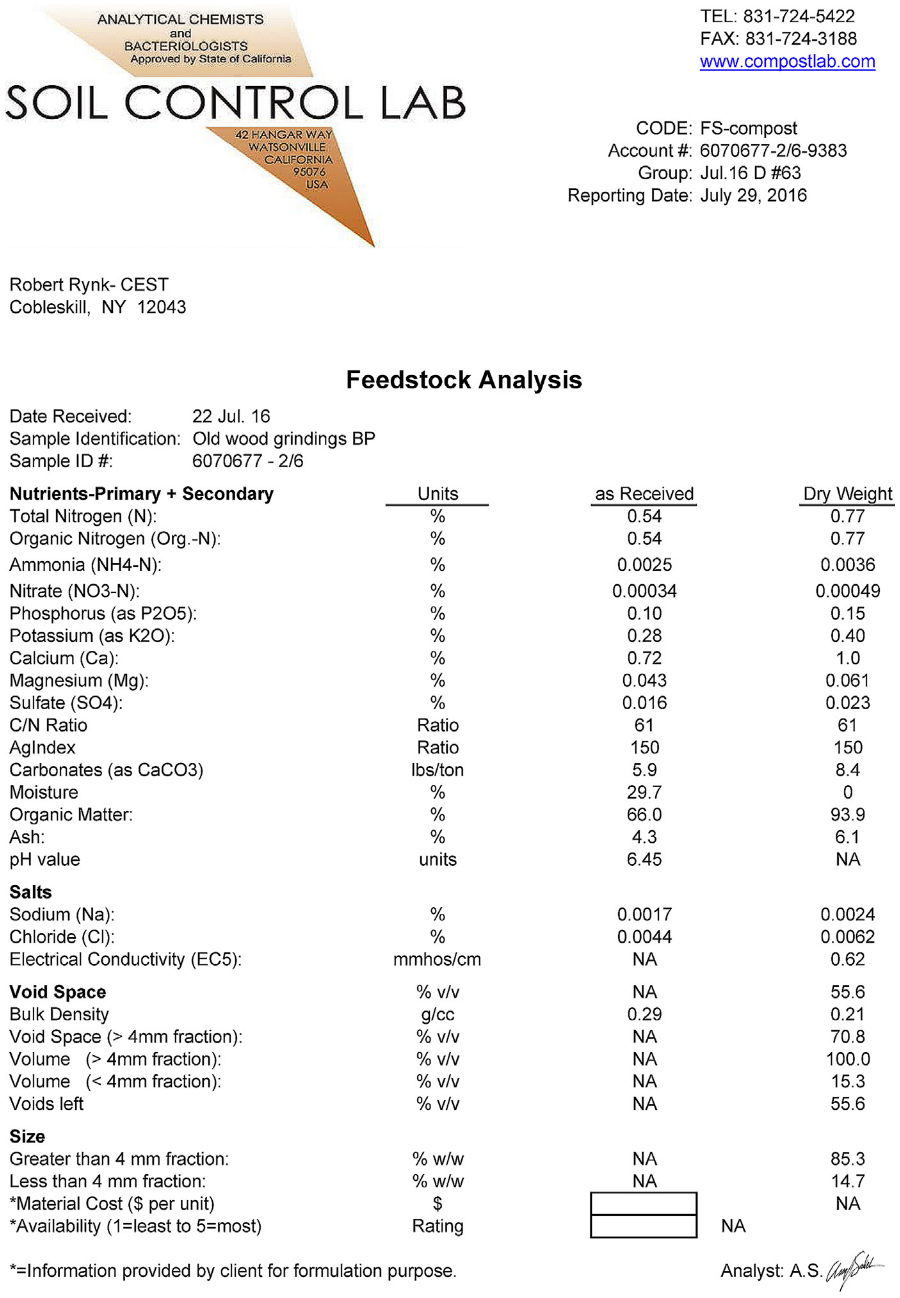
It is frequently helpful and sometimes necessary to determine the physical and chemical characteristics of specific composting feedstocks, current and prospective (Table 4.4). Knowing the characteristics helps in developing recipes, indicates a material's suitability for composting, infers the plant nutrient content of the compost, and identifies suspected contaminants. Values for some physical and chemical characteristics of many feedstocks can be estimated from experience or found in literature (as in Appendix B). Simple "in-house" tests can determine some qualities, like moisture content and bulk density. However, getting specific and reliable values for the concentration of nitrogen and other constituents requires the specialized equipment and skills of a professional laboratory (private or public). Testing for biological organisms (e.g., pathogens) and chemical contaminants also requires laboratory services. Professional laboratories possess the required knowledge of the methodologies, analytical equipment, technical skills, and quality control. Many labs that serve composting facilities offer analytical "packages" that bundle useful tests together for one price. When having feedstocks analyzed for compost recipes, it is advisable to secure a laboratory that conducts analysis specifically for composting feedstocks and compost.

The extent and frequency of laboratory analysis for feedstocks depend on the purposes for the analysis. The most common purpose is to provide information for developing composting recipes. In this case, a lab analysis should determine, at a minimum, the moisture (or solids) content, carbon concentration, nitrogen concentration, and organic matter content (or VS or ash). Laboratories usually break down the total amount of nitrogen by its primary chemical components—organic nitrogen and ammonia. Depending on the political jurisdiction and its regulations, some feedstocks, like municipal biosolids or MSW, may require testing for prescribed potential contaminants such as certain trace elements and biological constituents.

Table 4.4 Feedstock characteristics often or sometimes worthy of lab analysis.

Relevant to composting process and recipe	Indicators of compost product qualities and use	Environmental indicators (if required or otherwise warranted) [a]
Bulk density	Organic matter (or ash)	Heavy metals
Moisture content	Total nitrogen	Inert contaminants
pH	Organic nitrogen	Pesticide residues
Carbon content	Phosphorus	
Total nitrogen	Potassium	
Ammonia nitrogen	Calcium	
Phosphorus[a]	Magnesium	
Sulfur[a]	Sodium and chloride	
Organic matter (or ash)[a]	pH	

[a] *Rarely pertinent for evaluating feedstocks.*



ANALYTICAL CHEMISTS
and
BACTERIOLOGISTS
Approved by State of California

SOIL CONTROL LAB

42 HANGAR WAY
WATSONVILLE
CALIFORNIA
95076
USA

TEL: 831-724-5422
FAX: 831-724-3188
www.compostlab.com

CODE: FS-compost
Account #: 6070677-2/6-9383
Group: Jul.16 D #63
Reporting Date: July 29, 2016

Robert Rynk- CEST
Cobleskill, NY 12043

Feedstock Analysis

Date Received: 22 Jul. 16
Sample Identification: Old wood grindings BP
Sample ID #: 6070677 - 2/6

Nutrients-Primary + Secondary	Units	as Received	Dry Weight
Total Nitrogen (N):	%	0.54	0.77
Organic Nitrogen (Org.-N):	%	0.54	0.77
Ammonia (NH4-N):	%	0.0025	0.0036
Nitrate (NO3-N):	%	0.00034	0.00049
Phosphorus (as P2O5):	%	0.10	0.15
Potassium (as K2O):	%	0.28	0.40
Calcium (Ca):	%	0.72	1.0
Magnesium (Mg):	%	0.043	0.061
Sulfate (SO4):	%	0.016	0.023
C/N Ratio	Ratio	61	61
AgIndex	Ratio	150	150
Carbonates (as CaCO3)	lbs/ton	5.9	8.4
Moisture	%	29.7	0
Organic Matter:	%	66.0	93.9
Ash:	%	4.3	6.1
pH value	units	6.45	NA
Salts			
Sodium (Na):	%	0.0017	0.0024
Chloride (Cl):	%	0.0044	0.0062
Electrical Conductivity (EC5):	mmhos/cm	NA	0.62
Void Space	% v/v	NA	55.6
Bulk Density	g/cc	0.29	0.21
Void Space (> 4mm fraction):	% v/v	NA	70.8
Volume (> 4mm fraction):	% v/v	NA	100.0
Volume (< 4mm fraction):	% v/v	NA	15.3
Voids left	% v/v	NA	55.6
Size			
Greater than 4 mm fraction:	% w/w	NA	85.3
Less than 4 mm fraction:	% w/w	NA	14.7
*Material Cost ($ per unit)	$	☐	NA
*Availability (1=least to 5=most)	Rating	☐	NA

*=Information provided by client for formulation purpose.

Analyst: A.S.

FIGURE 4.8

Example of a typical laboratory analysis for a composting feedstock, in this case aged ground wood.

Courtesy of Soil Control Lab.

Typically, laboratory results also include analysis of pH, electrical conductivity (a measure of salinity), and concentrations of other nutrients such as phosphorus, potassium, calcium, magnesium, and sodium. Although not essential to developing a recipe, these characteristics can identify potential problems with composting or the compost products. Sulfur is not typically included in the suite of nutrients analyzed by laboratories. However, in some situations, a composter may wish to request it because the relative level of sulfur indicates the odor character of a given feedstock. Other tests that can be requested, as needed, include particle size distribution, feedstock degradability, lignin content, presence of pesticide or pharmaceuticals, and more.

Fig. 4.8 is a copy of a typical feedstock analysis report, in this case for ground wood. The report presents the values in two columns, "as Received" and "dry weight." The "as Received" column reports concentrations based on the actual or wet weight of the sample. Only moisture content, bulk density, and C:N ratio should be read from the "as Received" column. All of the other characteristics are regularly based on the "dry weight" concentrations. Figure 4.9 is an example of an abbreviated feedstock analysis, which this particular lab offered upon the request of this client. It is sufficient for the purpose of developing feedstock recipes.

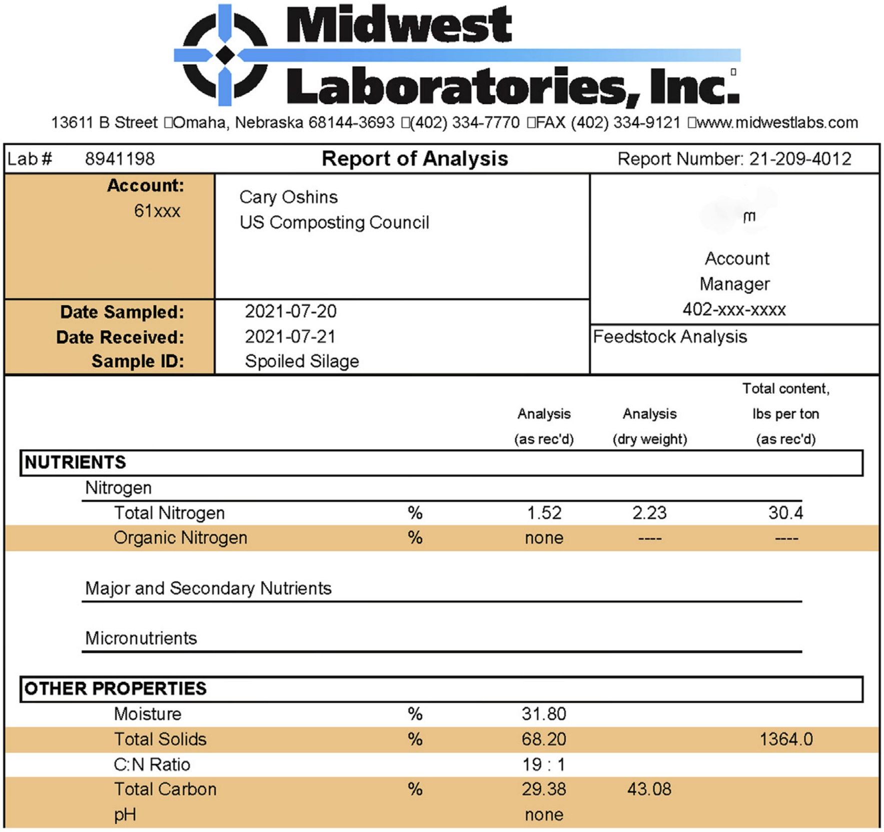
Whether tests are conducted in-house or by a laboratory, getting a good sample is an essential first step, followed by properly handling and preserving the sample. Sampling is especially important to accurately characterizing a feedstock. Most organic materials are notoriously heterogeneous; that is, they are inconsistent in their texture and composition. Furthermore, bulk materials tend to stratify, with the fines and moisture migrating toward the base of piles. A random sample from a pile of bedded livestock manure could yield a shovel full of mostly sawdust or a shovel full of mostly manure. The same situation could occur with a pile of mixed grass, leaves, and brush.

Chapter 14 offers more detailed information about sampling techniques, professional laboratory analysis, and in-house testing procedures.

8. Common feedstocks for composting

The list of organic materials suitable for composting is nearly endless. With the trend in managing organic residuals in a more sustainable way, more and different feedstocks are increasingly common. In particular, a variety of food residuals are being diverted for composting, either directly or after anaerobic digestion (AD).

This section summarizes the qualities of general categories of "the usual" composting feedstocks. Specific feedstocks within these categories are profiled in more detail in Appendix E. Table 4.5 very generally presents composting characteristics of common feedstocks. For each feedstock, listed there are exceptions to the characterizations presented in the table due to specific circumstances. The descriptions presented here are based on: numerous research publications; several composting manuals, guidebooks, and handbooks (e.g., Paul and Geesing, 2015); popular articles in *BioCycle* magazine, *BioCycle Connects*, and other periodicals; and the



Midwest Laboratories, Inc.

13611 B Street □Omaha, Nebraska 68144-3693 □(402) 334-7770 □FAX (402) 334-9121 □www.midwestlabs.com

Lab # 8941198	**Report of Analysis**	Report Number: 21-209-4012
Account: 61xxx	Cary Oshins US Composting Council	Account Manager 402-xxx-xxxx
Date Sampled: **Date Received:** **Sample ID:**	2021-07-20 2021-07-21 Spoiled Silage	Feedstock Analysis

		Analysis (as rec'd)	Analysis (dry weight)	Total content, lbs per ton (as rec'd)
NUTRIENTS				
Nitrogen				
Total Nitrogen	%	1.52	2.23	30.4
Organic Nitrogen	%	none	----	----
Major and Secondary Nutrients				
Micronutrients				
OTHER PROPERTIES				
Moisture	%	31.80		
Total Solids	%	68.20		1364.0
C:N Ratio		19 : 1		
Total Carbon	%	29.38	43.08	
pH		none		

FIGURE 4.9

Example of an abbreviated feedstock laboratory analysis with enough information for developing feedstock recipes.

Source: Midwest Laboratories, In.

experience of the authors and our colleagues. Many of these sources are listed in the “Consulted and suggested reading” section of this chapter.

Composting feedstocks are subject to substantially different regulations among different countries, states, provinces, and other political jurisdictions. In addition, various feedstocks are usually regulated differently within a given jurisdiction. It is important for facility managers and operators to understand, and follow, the regulations and guidelines that apply in their specific locations, especially in regard to safety and sanitization. For example, regulations that govern composting of animal by-products exist both across the European Union and in individual countries (see Box 4.3). With tiered levels of restrictions, these regulations apply to many common composting feedstocks, including manure, food wastes, and animal flesh.

Box 4.3 Composting regulated animal by-products

To borrow from the current vernacular, "animal by-products" are *literally* anything that arises from animals—manure, stomach contents (e.g., paunch manure), whole carcasses, partial carcasses, organs, hides, hooves, blood, bones, butcher waste, discarded meat, food waste that might contain meat (e.g., catering waste), and numerous other animal discards. They are of particular concern because of their *potential* to spread disease to humans or animals. As such, several countries thoroughly regulate the handling, treatment, and disposal of animal by-products.[3] These regulations impact composting (and AD) in ways that can dictate what feedstocks can be composted (e.g., no farm animal mortalities) and process sanitization requirements (e.g., temperatures/times). As the foregoing list of by-products suggests, many common composting feedstocks fall under these regulations where they exist including all animal manures and many, if not most, sources of food waste. Fortunately, the regulations do not require great changes to composting practices for most affected composters, especially for low-risk feedstocks like manures. Usually, the composting process easily meets the temperature and time mandates. The biggest burden may be related to sanitizing equipment and documentation.

The European Union has the most wide-ranging animal by-products regulations ((EC) No 1069/2009 and (EU) No 142/2011). Animal by-products are categorized according to their relative risk. Category 1 includes the highest risk materials like brain and spinal tissue that might carry prions that cause transmissible spongiform encephalopathies diseases like BSE (aka Mad Cow). Pet animals are also in this category. Category 1 materials cannot be composted. Category 2 and 3 materials can be composted following specified practices. Category 2 includes by-products like manure, paunch manure, and fish. Category 3 covers food waste and low-risk materials from slaughtering animals (e.g., hooves, feathers). The foregoing summary is an extreme simplification of the European regulation. The European Compost Network has a "Good Practice Guide" that explains and helps composters navigate these animal by-products regulations (Amlinger and Blytt, 2013).

---

[3] Current animal by-products regulations likely arose in response to catastrophic outbreaks of animal diseases in the 1990s and early 2000s, including foot-and-mouth, BSE (Mad Cow), and various swine and bird flus.

8.1 Yard trimmings

Also called green waste and yard waste, the category of yard trimmings covers a broad swath of materials including deciduous leaves, pine needles, grass clippings, unused fruits and vegetables, shrubs, tree branches, garden vegetation, aquatic plants, and other vegetative materials. A common thread among yard trimmings is that they are generated from maintenance of yards, gardens, parks, and other public and private landscapes. A stronger commonality is that they are largely vegetative in nature, and usually a varying mix of herbaceous and of woody vegetation. Depending on the amount and thickness of the woody materials, yard trimmings may require grinding before composting. Depending on the compost use, screening might be necessary.

It is more than a pun to proclaim that yard trimmings are the low hanging fruit*s* of composting feedstocks. They are easily composted with little oversight in residential backyards and other points of generation. In fact, on-site composting is the best approach to managing yard trimmings. Yard trimmings tend to amass in a somewhat balanced collection of moist green vegetation, dry brown vegetation, leaves, flowers, stalks, stems, branches green wood, and old wood. The mix is often, if not usually, ready for composting "as is." Most yard trimmings compost at a moderate rate—fast enough to produce compost within a normal composting cycle, yet slow enough to present a low risk of odors, again with important exceptions. One advantage for commercial and farm composters is that yard trimmings are typically someone's burden. These materials are offered up as composting feedstocks by property owners, public works departments, commercial landscape companies, and refuse haulers. Normally, they are a source of gate fees for commercial and municipal compost producers. At worst, they are available free, except possibly for the cost of trucking. Regulations for composting yard trimmings are relatively lenient, compared to other waste materials. In many jurisdictions, yard trimmings composters are not compelled to meet time/temperature requirements (e.g., PFRP). Nevertheless, it is prudent to achieve pathogen-killing temperatures because of the possible presence of pet wastes, weed seeds, and pesticide residuals. Fortunately, high temperatures are easily reached and maintained in commercial, municipal, and farm-scale yard trimmings piles and windrows.

Yard trimmings are not without drawbacks. They may contain soil, which does not impede composting but can accelerate wear on machine parts. If soil needs to be removed prior to grinding, the feedstocks can be run through a course screen to separate the soil particles. Yard trimmings often carry pesticides, weed seeds, plastics, and other possible contaminants. Weed seeds and most pesticides are effectively negated through the composting heat and biochemistry. Pyridine herbicides remain a potential problem with grass clippings (see Chapter 15). The degree of contamination with plastics and other inert objects depends on how yard trimmings are collected. Plastic bags are a large problem where property owners and landscapers use plastic bags to dispose of leaves, grass, and other yard trimmings. Paper bags should be encouraged as an alternative. Contaminants are prevalent in yard trimmings that are piled near the roadside for bulk collection. Such loads often include plastic shopping bags, food wrappers, tennis balls, hardware, car parts, and anything else that litters roadsides. Although most items can be removed by screening, loads of bulk yard trimmings should be inspected for large stiff items that could damage machinery.

Usually, yard trimmings arrive at the composting site as a mix of constituents that proportionally takes on the character of those constituents. That mix is very much dependent on the local region and its climate. Yard trimmings might be relatively uniform through the year or it can change drastically in amount and character through the seasons, especially in regions with cold winters. In the spring and early summer, moist green vegetation tends to prevail. The mix becomes dryer and browner starting in late summer and continuing through autumn. It may stop almost entirely in the winter. Generally, yard trimmings are balanced and diverse enough to compost well without adding other feedstocks. Dry vegetation and woody materials add good structure and lower the bulk density of mixed yard trimmings. Whether or not additional water must be added depends on the season, regional climate, and recent weather. Also, yard trimmings can serve as amendments for wet feedstocks. For instance, food residuals are often composted together with yard trimmings. However, when grass clippings are abundant, additional dry feedstocks may be needed.

Two particular types of yard trimmings are distinctive—deciduous leaves and grass clippings. In temperate climates, deciduous leaves standout because they tend to arrive over a relatively short period of time in the autumn. The composting site must be able to accommodate the huge autumn volume. Given the timing and annual cycle of autumn leaves, composters can adopt a relaxed schedule, allowing leaves to compost over the winter and into the spring and even summer. Leaves and partially composted leaves are also a good feedstock to compost with other materials, like grass clippings. Grass clippings are notable because they are a concentrated source of nitrogen, which contributes to their rapid decomposition. Without added amendments to balance the C:N ratio and promote aeration, grass clippings can generate odors.

8.2 Wood

Wood is generally available to composters as sawdust, shavings, chips, and large items including tree trunks, limbs, branches, pallets, and discarded lumber. These large items must be chipped, ground, or shredded at the composting site, if size reduction does not occur at the source.

Wood products are primarily valued in composting as amendments to absorb moisture and bulking agents to add structure and improve aeration. However, wood also brings a lot of organic matter to the process and compost products. Wood products have three overriding composting characteristics: (1) very low nitrogen concentrations (less than 0.1%) and thus very high C:N ratios (e.g., 400:1); (2) an inherent stiffness that gives most wood particles good structure; and, (3) a very slow rate of degradation, owing to the high lignin content.

When the particles of wood are very small, as with sawdust, the structure disappears and the rate of degradation increases but even small wood particles remain resistant to biological decomposition. The wood particles degrade at the edges, shrink in size, and change color but otherwise retain their basic characteristics and lend those characteristics to the compost. Large particles of wood remaining in the compost can be screened out and recycled for additional composting. Because wood resists degradation, only a fraction of the wood's carbon is released during composting. Therefore, the C:N ratio of a feedstock mix that includes wood is effectively overstated.

There is some variability among wood materials due to tree species and the specific condition of the wood. Generally, hardwood species degrade faster than softwood species, probably because softwoods tend to have more lignin. Wood with a larger proportion of sapwood, the peripheral living portion of the tree, has more nitrogen and moisture compared to wood that has relatively less sapwood. For example, freshly cut branches have proportionally more sapwood than large limbs, trunks, and dead branches. Dead trees and branches have no sapwood. Freshly cut, or "green," wood is relatively moist (50% to 60%) and then loses moisture after cutting. By the time they reach the composting pile, most woody materials are dry (20% to 30%). Wood waste from pallets, lumber, and other kiln-dried products is typically very dry, in the range of 10% to 20%.

8.3 Paper

Almost all paper is made from wood; wood that is pulped to very fine fibers and further processed to varying degrees. True to its wood origin, paper contains very little nitrogen. It can also be deficient in phosphorus. Consumer-based paper products that find their way to composting piles include newsprint, corrugated cardboard, and highly processed products like napkins, tissue, paper cups and plates, office paper and magazines. Discarded paper goods are generally extremely dry (less than 10%), although some paper items absorb additional moisture during use and transport. After paper takes on moisture, it starts to disintegrate into its fibrous constituents. Highly processed products, like office paper, are chemically stripped of lignin and, unlike wood, decompose quickly. Lightly processed paper products, like newsprint, are close to wood in composition and the fibers retain the biological qualities of raw wood. Corrugated cardboard, which has some structure built in by design, takes longer to physically collapse. It can provide structure to a compost pile for several weeks.

In addition, treatment of the water from paper manufacturing generates a solid residue or "sludge" that can be composted. Paper mill sludge is moist to wet (e.g., 60% to 80%), depending on the degree of dewatering.

8.4 Food waste

Food waste, also called food residuals, comes from residential collections, grocery stores, universities, schools, restaurants, hotels, hospitals, outdoor markets, fairs and festivals, separated organics, and warehouses. Mixed food waste from these sources can include both pre- and post-plate waste, vegetables, fruits, meat, milk, condiment containers, soiled food wrappers, food within wrappers, bottles and cans, plates, napkins, and other paper products as well as coffee grounds. Some may even include compostable service ware products such as utensils and clamshell packaging. One advantage of taking this type of waste is to help local schools and businesses manage their organic waste and possibly generate a farm to table (or store) relationship. However, one should be prepared for the "seasonality" of mixed food waste from these sources. Secondary schools produce waste only 10 months of the year and food waste type depends on what is abundant at that time of year. One week's load may be mostly pineapple tops, while other loads may have only discarded pizza dough and cardboard.

Because there is such a range, it is difficult to characterize food waste. Sources should be evaluated on an individual basis. By itself, and very generally, the food component of food waste is moist to wet (60% to 80%), moderately high in nitrogen (1% to 3%) and decomposes quickly. Again, these characteristics are very dependent on the actual composition. Paper products within the food lower the moisture and nitrogen concentrations and give the food some structure for aeration. Paper and cardboard are usually not a problem for composting but the plastic and other inert items must be removed. The best place to separate these contaminants from the food is at the source, which merits strong communication with the generator and may require placing restrictions on the contents of the food waste loads. Increasingly, depackaging machines are being used to separate the food from wrappers and containers.

Taking on food waste raises the management bar for composters, at least compared to yard trimmings, the feedstock that is usually composted with food. In addition to the potential contamination, food decomposes quickly and is attractive to flies, rodents, and other animals. It is often unsightly and can become odorous, even before it arrives at the composting site. Therefore, some level of containment is necessary for food waste composting. The containment can be in outdoor piles if the food is mixed with abundant yard trimmings or other amendments. The food should remain within the envelop of the pile, and the pile should not be turned until the food decomposes to the point at which it is no longer a nuisance. Alternatively, the pile can be turned and then covered with amendment or finished compost. Otherwise, food waste can be initially composted in rotating drums, aerated containers, or other in-vessel systems until the food essentially disappears. The main advantage of adding food waste to yard trimmings or manure composting enterprise is that the composter can charge a fee for handling the food waste. However, it also tends to increase the regulatory burden.

8.5 Biosolids

Biosolids is the label used in the United States for treated sewage sludge that can be recycled by land application and composting. Sewage sludge is the accumulation of microbial biomass and other organic solids generated at wastewater treatment plants. Biosolids usually derives from the anaerobic or aerobic digestion of the sludge. Biosolids has a long history as composting feedstock. Fairly well-established procedures and recipes have been developed for composting biosolids. Generally, biosolids is nitrogen-rich (2%−7%) and very wet (70%−85% moisture). The nitrogen and moisture content depend on the dewatering and treatment processes at the wastewater plant. Composting biosolids requires two to four volumes of dry amendment per volume of biosolids. Typically, the amendment used is wood chips, which is commonly screened from the compost and reused for additional batches of biosolids.

Biosolids is a good feedstock for making nutrient-rich compost but it comes with “baggage.” Biosolids is a highly regulated material. Composting it involves operational and site permits, process monitoring, and product analysis. It is mandatory for composters to demonstrate pathogen destruction, either by maintaining records of process temperatures or by product testing (or both). Depending on the initial quality of the biosolids, regulations governing compost use might apply due to heavy metal concentrations. Also, biosolids presents a moderate to high risk of odors. A well-buffered site, process controls and/or containment are necessary to control odors. For these reasons, biosolids has a public image problem and a composter may meet stiff resistance from the community. For the same reasons, there is a good opportunity to collect fees for composting biosolids.

8.6 Livestock and poultry manure

Manure generated from livestock and poultry farms can be tricky to characterize because it arises in different forms, depending on the animal species, husbandry practices, manure collection approaches, climate, and processing. The various sectors of livestock and poultry industries tend to follow similar manure management practices, as a group. Still, there are large difference between farms in any given sector.

As excreted by the animal, manure is wet and has a relatively high nitrogen content. As-excreted moisture content ranges from about 75% for poultry, sheep, and horses to 90% for cattle and swine. Nitrogen concentrations start at about 2.5% for horses and can surpass 6% for poultry and swine. Ultimately, the consistency and nutrient content of manure depends on the husbandry practices.

One primary factor is the amount of bedding or litter used in the animal rearing areas ("litter" is bedding for poultry). Bedding/litter is typically dry fibrous by-products like straw, sawdust, wood shavings, nut shells, rice hulls, chopped corn stalks, shredded paper and the like—the same types of materials that make good composting amendments. Bedding can dilute the nitrogen concentration by one-third to one-half or more. Moisture contents of bedded manure range from 50% to about 80%. Where bedding or litter is used generously, the manure tends to be solid and might be compostable without additional amendments. Where bedding is used sparingly, manure tends to have a wet porridge-like consistency and is often referred to as a "slurry." The moisture content of slurry is in the 80% to 90% range. Slurry can be composted by creating a trench down the center of a prebuilt windrow with periodic dams to slow the movement of liquid so it can be absorbed.

Manure consistency is also determined by how and how often manure is collected. Horse stalls tend to be cleaned regularly by stable hands with manure forks. Horse manure is typically 50% to 70% moist due to the large amount of bedding being removed. Manure that accumulates over time beneath the animals for weeks or months is usually liberally bedded and tends to be solid, in the 60% to 70% moisture range. This form of manure is commonly called a "bedded pack" on livestock farms and simply "litter" by poultry producers. It is commonly gathered-up with skid-steer or tractor buckets. Their composting characteristics depend on how much bedding is applied, the climate, and whether the bedded pack is located under a roof or not.

At the other extreme, some livestock farms remove manure from barns by flushing the floors with water. Flushed manure is truly liquid and not suitable for composting in its liquid form, except as a supplemental moisture source. However, liquid manure is frequently squeezed and screened to separate the solids from the liquid. The solids portion, which is dominated by wasted feed and bedding, can have a surprisingly high C:N ratio (e.g., over 30:1). Moisture content typically ranges from 70% to 85%, depending on the method of separation and also the climate. These solids are good composting feedstocks. They are often partially composted on the farm to sanitize them before being recycled as bedding.

The weather greatly influences the characteristics of manure, especially where animals are raised and fed outdoors. An abundance of sun and wind reduces moisture while an abundance of rain adds water and washes away nutrients and salts. Loss of ammonia nitrogen is increased by sun, wind, and warm temperatures; cold temperatures conserve it. In addition, manure from dry lot dairy farms, beef feedlots and other animals confined to unpaved feedlots, and paddocks tend to include a fair amount of soil that is scraped up with the manure. The soil increases the manure's density and ash level, which consequently lowers the organic matter.

While manure is a natural composting feedstock, it is not without a few potential concerns. Many manures have relatively high levels of salt, pH, and ammonia, which can be a detriment in some situations There is a "silver lining" in the fact that the high salt levels are primarily attributed to high levels of nutrients. Depending on the source, manure can carry unwanted debris like medicine containers, trash, and scrap metal. However, it is generally free of the plastic contamination common to yard trimmings and food waste. Manures carry weed seeds, parasites, and likely contain some traces of antibiotics and other medicines. These biological contaminants are reliably killed and/or decomposed during thermophilic composting.

Some types of manure are also possible sources of the persistence pyridine herbicides like clopyralid, aminopyralid, and picloram. These herbicides may be used on animal feed and forage crops, especially grass hay but also on sugarbeets, wheat, and mint. It is worth noting that damaging levels of these herbicides have been found in cattle and horse manure.

8.7 Agricultural crop and processing residue

The production of farm crops, and value-added products, generates a number of organic by-products that are not necessarily applied back to crop land. Prominent examples include straw, hay, spoiled silage, wasted feed, corn stover, corn cobs, bagasse, culled fruit and vegetables, rice hulls, nut shells and pomace from pressing olives, apples, grapes, and other crops. Some of these materials may come from locations beyond the farm fields, including packing houses, storages, markets, and processing facilities.

As a category, the composting characteristics of agricultural residues cannot be generalized because they are specific to the materials at hand. One group of residues is consistently dry, low in nitrogen, and decompose moderately well (e.g., straw, corn stalks, bagasse). They make good amendments for composting with wet feedstocks like most manures. Some residues in this group also have a particularly strong structure and make good bulking agents (e.g., nut shells, rice hulls). Another group is generally wet, nitrogenous, and degrades quickly (e.g., unused fruits, vegetable culls, spoiled silage). These materials need to be combined with drier feedstocks for composting.

In general, agricultural crop residues are clean feedstocks that decompose well and present little odor risk. However, it is important that agricultural residues are composted at thermophilic temperatures. Most agricultural by-products carry plant pathogens, weed seeds and, in some cases, pesticide residues. Each material should be evaluated separately to determine its applicability as a compost feedstock.

8.8 Food processing waste

A wide variety of by-products from food processing make good feedstocks for composting. Some examples of food processing by-products that have been composted include potato peels, wasted pasta, filter press cake from cranberries and other fruits, spent brewers' grain, almond hulls, tomato paste, corn cobs, olive mill pomace, spent coffee grounds, gelatin waste, out-of-date beverages, and seafood processing waste (see below). These by-products differ greatly from one another; for instance, ranging from dry solids (e.g., peanut shells) to completely liquid (e.g., cheese whey). Therefore, each type must be evaluated on its own. Meat processing and butchering wastes carry special restrictions. Composting of butcher waste should follow the same procedures as composting animal mortalities, which are discussed in Chapter 8.

Many food processing by-products still have food value and can be attractive to flies, rodents, birds, and other animals. Such by-products must be composted in a contained manner, as previously described for food waste. The odor risk depends entirely of the specific material and ranges from low to moderate (e.g., pomace) to potentially high (e.g., gelatin waste). Compared to commercial and residential food wastes, food processing products are relatively free of contaminants. However, some by-products may contain source-specific contaminants like machinery and cleaning solutions used at the processing plant and poorly degradable additives such as filtering and pressing aids (e.g., diatomaceous earth, rice hulls). Because a feedstock comes from a single generator, contamination is relatively easy to correct, compared to consumer and commercial food wastes. A major advantage of food processing by-products is the opportunity to receive a tipping fee.

8.9 Fish and seafood processing waste

Fish and seafood wastes includes whole fish, racks, frames, heads, tails, crustacean and mollusk shells, and ground-up mixed fish waste (called "gurry" in some regions). Some packing operations may even generate associated by-products like wasted bread crumbs. Fish and seafood wastes have a long history of composting. Few other recycling alternatives can economically take advantage of their rich nutrient content and the nuisance factors that fish and seafood wastes present. These materials usually come with a tipping fee for the composter.

Most fish wastes are wet to very wet (70% to 90%). Almost all fish wastes are high in nitrogen (between 7% and 15%), giving them a very low C:N ratio. Lobster, crab, shrimp, and mollusk shells, with an average of about 50% moisture, are drier than fish waste. The shells retain enough meat and nitrogen to still give them a low C:N ratio. The shells provide good structure to a compost pile. The crustacean shells decompose during composting; mollusk shells do not decompose at all, although they may become more brittle with thermophilic temperatures. Fish flesh decomposes very rapidly and quickly generates putrid amine-related odors. Bones are slower to decompose but generally disappear during composting.

Fish and seafood waste must be handled in manner that minimizes odor and discourages birds, flies, and other pests. A composting recipe that includes fish and seafood requires a large amount of chunky, dry amendment to reduce odor, and absorb moisture. As with other food wastes, fish and seafood items need to be isolated from the surrounding environment until they are well-decomposed.

8.10 Anaerobic digestate

AD is a popular treatment option for manure, sewage sludge and, increasingly, food waste. It recovers biogas energy from these organic feedstocks but leaves behind most of the volume and nutrients of the feedstocks in the "digestate," the partially stabilized effluent of digestion. Regardless of the feedstock, digestate can be composted to increase its value and broaden its potential uses. Municipal biosolids, which has a long history of composting, is the digestate of anaerobic digestors at the wastewater treatment plant.

Digestate reflects the characteristics of the feedstocks from which it is made. Relative to the raw feedstock mix, organic matter, carbon and solids concentrations decrease but the volume diminishes only slightly, becoming slightly more liquid. Nearly all of the plant nutrients entering with the feedstock remain in the digestate, although much of nitrogen changes from organic to ammonia nitrogen. With the conservation of nitrogen and the loss of carbon, the C:N ratio decreases slightly. AD reduces pathogens and the viability of weeds but does not eliminate them unless the digestion process is thermophilic, which is uncommon. The digestate is somewhat more biologically stable than the raw feedstock, which means it is slower to decompose. Still, digestates typically retain enough degradable organic matter to decompose well and generate heat during composting. One advantage of digestate is that it tends to be less odorous than the raw feedstocks. Many of the volatile odorous compounds formed, like hydrogen sulfide, leave with the biogas.

Digestate that results from "dry" AD systems are moderately wet with moisture contents in the range of 60% to 80%. Most AD systems, however, process dilute wet feedstocks and produce a digestate in the range of 90% to 95% moisture. This digestate can serve as a source of moisture for composters in arid climates. However, usually digestate is separated into liquid and solid fractions. The solid fraction, at 75% to 80% moisture, is composted. In this case, most of the nitrogen in the digestate is carried in the liquid fraction, thereby by-passing the compost.

Much of the nitrogen in either fraction of digestates is in the ammonia form, which readily volatilizes. Therefore, high N digestates are best combined with abundant low-N and low-pH feedstocks, preferably those with available carbon (e.g., straw rather than wood). Also, turning and other modes of agitation should be minimized in the first few weeks of composting to avoid exposing the interior of the pile, where the ammonia is concentrated, to the outside environment.

8.11 Compostable plastics

With compostable plastics, more food wastes can be captured and composted without the effort of separating plastic contaminants or sacrifices to compost quality; at least that is the hope. Over the past decade, many technological and strategic advances have made compostable plastics a reality for the composting industry. However, their widespread acceptance remains frustrated by several challenges (Box 4.4).

Box 4.4 The promise and perils of compostable plastics

Author: Matthew Cotton

Plastic products that thoroughly decompose during composting offer the promise that food residuals, and other organics, can be widely composted without the worry and inconvenience of physical contamination. This promise has yet to be fully realized, even though great strides have been made in creating compostable plastic products. Industry can make plastics that decompose under standardized composting conditions. A number of products have been certified to do so. However, peripheral factors, beyond the chemistry and design of the plastic products create confusion and hinder the potential of compostable plastics (EEA, 2020). Such factors include sporadic and inappropriate use, lack of identification, and variability of composting practices.

The promise of *compostable* materials is that they may function just like plastics in their primary use, especially in food service applications—like plates, cups, and bags—thus making the separation of food for composting more productive. However, there are several challenges to the composter who would accept and process these materials. And in the end, replacing single use disposables with single-use compostables does not necessarily reduce their environmental impact.

Although there are still questions to be addressed about how quickly compostable plastics break down in a well-managed compost system, there are larger, fundamental questions which offer perhaps greater challenges:

Identification Compostable plastics look nearly identical to their noncompostable counterparts. Regular plastics are a contaminant that most composters strive to avoid, and spend considerable time and money trying to remove before they compromise finished products. It can be extremely difficult for composters to separate the compostable from the noncompostable materials. Depackaging machines, which some composters use as part of preprocessing can remove significant amounts of contaminants in a food waste stream, but the technology does not differentiate between compostable and noncompostable. The same is true of a back-end screen. Some have hoped to overcome the identification problem with a single bold choice of color or design, like a green stripe or a consistent color. Unfortunately, many of the large national food manufacturers have invested in branded color schemes that (in their minds) conflict with a green stripe, and there's nothing stopping traditional plastics manufacturers from making copycat items. This widespread confusion leads to the majority of compostable plastics collected with food being removed and disposed of, wasting the opportunity for them to be composted.

User confusion Compostable products are evolving at a time when compost infrastructure is not consistently developed in the United States. Once a Starbucks user learns that their coffee cup, lid, and stirrer or straw goes in the compost bin, they may think ALL coffee cups, lids, etc., go in the compost bin. Some composters readily accept them, and some avoid them as much as they can. This confusion leads to noncompostable items being put in compost bins and vice versa.

Organic certification Getting compost approved for use by certified organic farms is an important market for some composters. Even some composters who sell to conventional growers go through the effort to get their products approved for organic use as a marketing tool. Organic certification is a powerful imprimatur. The US Department of Agriculture's National Organic Program currently views compostable plastics as synthetic and while the use of compostable plastics in compost is not expressly prohibited, many certifiers will not approve a compost that contains compostable plastic, unless it can be demonstrated that the plastic materials are removed.

Compost residence time How long a compost process takes, from raw feedstocks to finished product, varies considerably among facilities, but in general, compost residence times are shrinking as facilities handle more and more feedstocks and become more proficient in managing the process. The lab tests developed to ascertain "compostablilty" assume disintegration in 12 weeks and complete biodegradation in 180 days. Many composters make compost in much faster time frames, leaving compostable materials inadequate time to break down.

Box 4.4 The promise and perils of compostable plastics—cont'd

Therefore, if "compostable" plastics are included in the compost process, a composter should make sure the products, at a minimum, meet the specifications for "compostable" products. Products that meet these standards can be identified by the "Compostable" Logo stamped on the products. In addition, it is wise to test a compostable product on a small scale in the composting operation to see if it disintegrates and/or biodegrades well enough within in the required time and under your conditions. For example, if compost is to be used or sold in 90 days and the plastic takes 180 days to completely disintegrate and biodegrade, that particular product may be problematic. Any composters considering accepting compostable plastics should seek as much information as possible and evaluate manufacturer claims with skepticism considering all of the possible implications of accepting these materials.

There are several types of plastics resins that are designed to be "biodegradable." Polylactic acid (PLA), made by fermentation of agricultural materials, is probably the most recognizable and most common. Others are derived from starches (e.g., polyhydroxyalkanoate or PHA) and cellulose (e.g., cellophane). These and other resins are used to manufacture a variety of biodegradable products, such as bags, wrappers, food utensils, containers, drinking cups, and films for agricultural mulch. Although the resins used and a product's function might suggest how well a given product decomposes, these features are not good enough predictors. Testing is still necessary.

People often use the terms *degradable*, *biodegradable*, and *compostable* plastics[4] interchangeably, but they are not the same. Under the conditions, and in the duration of, a composting pile, the "degradable" and "biodegradable" plastics may not completely degrade. Most operations sell their compost after 6 to 12 months, so "compostable" plastics must reach significant levels of biodegradation in these time frames. Otherwise, they are noticeable in the finished compost or they wind up being screened out prior to sale. What composters need are products that are explicitly "compostable."

Several standards now exist for determining whether a biodegradable plastic product is acceptably compostable. Generally, to earn this label, the product must: (1) disintegrate rapidly under thermophilic composting conditions; (2) biodegrade completely during composting or shortly after the finished product is used at a rate that is consistent with other materials composted; (3) generate no toxic compounds that can destroy the utility of the compost; and (4) not contain high levels of regulated metals. In Europe, EN 13432 is the standard for packaging products (EEA, 2020). In the United States, the corresponding standards are published by the American Society for Testing and Materials (ASTM). The standards are ASTM D6400 (specification for compostable plastics) and ASTM D6868

---

[4] The term "bioplastics" is intentionally excluded here. Bioplastics infers that the plastic resin has been derived from biological materials. It does not mean that the resulting product is degradable, biodegradable, or compostable (van den Oever, 2017).

FIGURE 4.10

Compostable products logo certified by the Biodegradable Products Institute.

Source: Biodegradable Products Institute, www.bpiworld.org.

(specification for biodegradable plastic used on paper and other compostable substrates). The ASTM specifications guarantee that there is no more than 10% of the product remaining on a 2 mm sieve after 12 weeks of composting (disintegration), that at least 90% of the plastic is converted to carbon dioxide in 180 days or less (biodegradation), the final product supports plant life when compared to comparable control compost (compost utility) and the final product does not have concentrations of regulated metals greater than 50% of federal mandates in the country where the products are sold. Products that meet compostable standards can be identified with a logo issued by a recognized industry organization or public authority. For example, in North America, the logo shown in Fig. 4.10 is certified by the Biodegradable Products Institute (BPI, 2020). Depending on the certifying organization, other restrictions may also apply. For instance, BPI prohibits the use of PFAS and restricts the use of carcinogens, reproductive toxins, and mutagens (CRMs).

8.12 Inorganic and organic extras

Some composters include miscellaneous and mostly inorganic ingredients to a composting mix. Examples include chemical fertilizers, lime, soil, peat moss, biochar, and recycled compost. In some cases, such materials are added to improve the composting process or product. A few additives, including biochar and zeolite, have been reported to reduce ammonia loss or greenhouse gas (GHG) emissions (see Chapter 11). In other cases, the motivation is to gain a fee for composting harmless by-products that need an outlet. Wood and coal ash and gypsum are examples in this case. Each of these materials has its own character and influence in the composting pile.

Fertilizer and urea, or other concentrated nitrogen sources, are sometimes added to lower the initial C:N ratio of a composting mix. While fertilizer does add nitrogen, and often speeds the process, the benefits are short-lived. Nitrogen from such sources tends to be available much more quickly than the carbon in the organic materials. Initially the available carbon and nitrogen are in balance; but as the easily available carbon is depleted, a surplus of nitrogen soon develops. Eventually the excess nitrogen is lost as ammonia.

Lime is added either to adjust pH upward or to control odors. Lime is rarely a necessary ingredient, as pH adjustment is rarely necessary, and can be detrimental. If lime is used for odor control, it can raise the pH enough to cause an excessive loss of ammonia. The odor-reducing effect of lime is temporary, and it requires a great deal of lime. The same effects should be expected for other concentrated sources of alkalinity, including cement kiln dust and wood ash.

Soil, especially clay soil, is a recommended ingredient for certain approaches to composting. The purpose of the soil is to provide additional microscopic surfaces for microorganisms to inhabit and metabolize the organic feedstocks. Clay also has the ability to hold onto positively-charged nutrients (i.e., cations). Also, advocates believe clay encourages humus accumulation. These purported benefits are not universally accepted. Still, adding soil has certain effects, both good and bad. On the positive side, soil helps to moderate moisture and temperature within the pile. It also adds weight to the finished compost, making the product feel more soil-like. Conversely, the soil decreases the organic matter level and raises the ash content. Abundant soil decreases the porosity and increases the bulk density of the composting mix. In short, adding soil is unnecessary but can help achieve specific aims.

Peat moss is an acidic fibrous material which has resulted from years of anaerobic decomposition beneath water or water-logged soils. It is low in nitrogen and highly absorbent of water, nutrients, and odors. It may hold over 10 times its weight in water. Except in regions where natural deposits exist, peat moss is expensive, partly because of its competing uses as an amendment for potted plants and other horticultural crops. Peat moss passes through the composting process virtually unchanged, producing a potentially high valued compost. Its odor- and water-absorbing qualities make it an excellent amendment, but cost limits its use.

Biochar is the dry charcoal-like residue obtained from "burning" biomass (usually wood) with insufficient oxygen so that combustion is incomplete and much of the carbon is retained. Biochar has abundant micropores and surfaces for adsorbing chemical compounds. It is normally promoted as a soil amendment, by itself and in combination with compost. However, it has also been proposed and used as an amendment for composting feedstocks. When used as a feedstock amendment, the main potential benefits of biochar are absorption of moisture, lower emissions of ammonia and GHGs and enhancement of the compost product (precharged with biochar). The carbon in biochar is largely unavailable to microbial decomposers. Research studies have generally shown that biochar can provide these benefits when the biochar comprises 2%—10% of the composting recipe, by volume (Camps and Tomlinson, 2015). However, there are several variables to consider including the relative amount of biochar used and the qualities of the biochar itself (e.g., how it was made and from what feedstocks). Overall, biochar appears to be a positive feedstock amendment, depending on the cost to purchase and handle it.

Wood ash is very dry with little or no carbon and nitrogen. It contains a fair amount of other nutrients, particularly potassium. The concentrations of trace metals may be a concern with some ash. In a composting mix, wood ash absorbs moisture. Like lime, it raises the pH of the mix and has also been used as an odor reducing agent. Handling is difficult as the ash is a fine powder which blows around and creates dust. Particles tend to cement together after they become wet. Wood ash can be used as a composting amendment for wet acidic mixes or for increasing the level of nutrients, especially potassium. It should not be used if the pH of the mix is already high.

Coal ash is what is left over after burning coal for fuel. Like wood ash, it is very dry and powdery but otherwise it differs from wood ash in content. Coal ash basically consists of oxides of silicon, aluminum, titanium, iron, calcium, magnesium, potassium, and sodium. It also contains molybdenum, sulfur, and a myriad of other elements that may be of concern. A 1994 study at Washington State University composted coal ash with manure and found the final product to show poor growth in greenhouse bioassays, but increased barley yield in field applications. Unless there is a real need for disposal of waste coal ash and a large tipping fee is involved, it is probably best to keep this out of the compost pile.

Zeolites are a group of minerals classified as aluminosilicates. Many types of synthetic zeolites are manufactured with different specific properties, while natural zeolites are mined, with properties that depend on the mineral deposits. They are used in a wide variety of applications from cat litter to water filtration.

Zeolites have very porous microstructures and high cation exchange capacities. They offer abundant internal surfaces that hold onto water, nutrients, and other compounds. Consequently, zeolite is of interest as an additive to limit the mobility of trace elements and reduce emissions of GHG and ammonia during composting, during storage and land application of raw manure, and as an agricultural soil amendment (Cataldo et al., 2021). In research studies for composting applications, zeolites have been applied both as a thin blanket (e.g., 2–4 cm or 1–2 in.) and as a component of the feedstock mix. Typically, zeolite comprises 5% to 10% of the mix on a dry weight basis (Soudejani et al., 2019). As Chapter 11 details, research results have generally reported substantial reductions in emissions.

The primary question regarding zeolite is the cost to obtain and handle it. On a per unit basis, the cost of zeolite products appears to be inexpensive. However, the large volumes required in composting applications can amount to a large expense.

Most of the *gypsum* available to composters is from wasted drywall, a layer of gypsum, 12–20 mm thick ($^1/_2$ to $^3/_4$ in.) sandwiched between thin sheets of paper. Also called, sheet rock or wallboard, it is generated in large quantities by construction and demolition activities. Therefore, composting drywall is considered a recycling option. Drywall needs to be broken up into small pieces before being composted. While the paper decomposes during composting, the gypsum merely disintegrates and adds its minerals to the compost. Gypsum is very dry with a moisture content around 5% and has almost no nitrogen. Gypsum is basically calcium sulfate, so the amounts of both calcium and sulfur increase in the finished compost. The additional sulfur can increase the emissions of sulfur-based odors. For the composter, the primary benefit of gypsum is the potential fee for taking waste drywall. It has little biochemical effect on the process, although gypsum has been reputed to reduce ammonia volatilization during manure and biosolids composting. Gypsum does not lower or raise pH, but it may change the consistency and feel of the compost.

Table 4.5 General and typical qualities of common composting feedstocks.

Feedstock	Moisture content	Nitrogen content	Bulk density	Structure	Degradability	Odor risk	Contamination concern	Notes
Yard trimmings (green waste)								
Mixed yard trimmings	Moderate	Moderate	Low-mod.	Good	Poor-fair	Low	Moderate	1,2
Deciduous leaves	Moderate	Moderate	Low	Good-fair	Good	Low	Moderate	2
Coniferous needles (e.g., pine)	Low-mod.	Moderate	Moderate	Fair	Good	Low	Low	3
Grass clippings	High	High	High	Poor	Good	High-mod.		4
Seaweed and aquatic plants	High	High	High	Poor	Good	Low-mod.	Low	2
Brush	Moderate	Low-mod.	Low	Good	Poor-fair	Low	Low	1
Wood and paper								
Wood and bark chips	Low-mod.	Very low	Low	Very good	Poor	Low	Low	5
Wood shavings and sawdust	Low-mod.	Very low	Low	Good	Poor	Low	Low	5
Waste paper	Very low	Very low	High-mod.	Poor	Good-fair	Very low	Low-mod.	6,7
Corrugated cardboard	Low	Very low	Moderate	Fair	Fair	Very low	Moderate	6
Paper mill sludges	High	Low-mod.	Low	Poor	Good-fair	Moderate	Low	

Continued

Table 4.5 General and typical qualities of common composting feedstocks.—*cont'd*

Feedstock	Moisture content	Nitrogen content	Bulk density	Structure	Degradability	Odor risk	Contamination concern	Notes
Municipal waste								
Biosolids	High	High	High	Poor	Good	High-mod.	High-mod.	8
Mixed solid waste	Low-mod.	Low-mod.	Moderate-low	Moderate	Moderate	High	Very high	9,10
Animal manure								
Caged poultry	High-mod.	Very high	High	Poor	Good	High	Low	11
Floor-raised poultry	Low-mod.	High	Moderate	Moderate	Good	High-mod.	Low	11,12
Dairy cattle	High-mod.	High-mod.	High-mod.	Moderate	Good	Moderate	Low-mod.	12,13,15
Beef cattle	High-mod.	High-mod.	High-mod.	Moderate	Good	Moderate	Low	12,13,14
Horses	Moderate	Moderate	Moderate	Moderate	Good	Low-mod.	Low	12
Goats, sheep, rabbit	High-mod.	Moderate	High-mod.	Moderate	Good	Low-mod.	Low	12,16
Swine	High	High	High	Poor	Good	High	Low-mod.	12,13,15
Fish manure (aquaculture)	High	High-mod.	High	Poor	Good	Moderate	Low	17

Agricultural crop and processing residuals								
Hay	Low	Low-mod.	Low	Good-fair	Good-fair	Low	Low	11,18,19
Straw	Low	Low	Low	Good	Moderate	Very low	Low	18,19
Corn stover	Low	Low	Low	Good	Moderate	Very low	Low	18,19
Bagasse (e.g., sugarcane)	Low-mod.	Low	Low	Good	Moderate	Low	Low	11,18
Spoiled silage	High-mod.	Moderate	High-mod.	Moderate	Good	Moderate	Low	11,18
Rice hulls	Low	Low	Low	Good-fair	Poor	Very low	Low	
Nut shells	Low	Low	Low	Good	Moderate	Very low	Low	
Cotton gin trash	Low-mod.	Moderate	Moderate	Moderate	Good-fair	Low	Low-mod.	
Cranberry plant residues	Moderate	Low-mod.	Low-mod.	Moderate	Good-fair	Very low	Low	3
Culled fruit and vegetables	High	High-mod.	High	Poor-fair	Good	Low-mod.	Low	20
Potato culls	High	High-mod.	Low-mod.	Poor	Good	Low-mod.	Low	20
Apple, grape and cranberry filter cake	High-mod.	Moderate	Low-mod.	Poor	Good	Low-mod.	Low	21

Continued

Table 4.5 General and typical qualities of common composting feedstocks.—*cont'd*

Feedstock	Moisture content	Nitrogen content	Bulk density	Structure	Degradability	Odor risk	Contamination concern	Notes
Food waste								
Mixed food waste	Low-mod.	High-mod.	Low-mod.	Poor-fair	Good	High	High-mod.	22, 23
Food processing wastes	High-mod.	High-mod.	High-mod.	Poor-fair	Good	High-mod.	Low	22
Spent brewers' grains	High	High-mod.	High-mod.	Poor	Good	Moderate	Low	24
Waste beverages	Very high	Very low to none	Liquid	Liquid	High	Very low	Low	25
Fish and seafood								
Fish waste (e.g., frames, tails, dead fish)	High	Very high	Low	Poor	Good	High	Low	26,30
Fish gurry	Very high	High	Liquid	Liquid	Good	High-mod.	Low	27,30
Crustacean shells	Moderate	High	Moderate	Moderate	Good-fair	High	Low	28
Mollusk shells	Moderate	High-mod.	Low	Good	Poor	High-mod.	Low	29
Meat residuals								
Butcher and meat packing waste	High	Very high	Low	Poor-fair	Good-fair	High	Low	26,30
Blood	High-mod.	Very high	Low	Liquid	Good	High	Low	30
Paunch manure	High	Moderate	High-mod.	Moderate	Good	Moderate	Low	31

[1] *Characteristics depend on the relative mix of woody and vegetative materials. The characteristics moderates with more vegetation.*
[2] *Physical contaminants like metal hardware, plastic bags, and other litter can occur with curbside collection.*
[3] *Can have a low pH (acidic).*
[4] *May carry residues of persistent pyridine herbicides.*

[5] Products derived from green wood have moderate moisture and low odor risk while those made from dried lumber (e.g., pallets) have a very low moisture content and odor.

[6] Various types of wastepaper exist. Newsprint retains lignin and is therefore less degradable than other types of waste paper. Magazines have a high ash content due to the use of clay to impart a gloss.

[7] Flat items, like sheets of paper, can stick together in layers, giving them a higher bulk density.

[8] Some sources of biosolids may have high concentrations of trace metal.

[9] Mixed solid waste is heavily contaminated with physical and some chemical contaminants and needs, which requires substantial pre- and/or postseparation operations.

[10] Characteristics depend on the relative amount of paper included. Paper moderates the characteristics.

[11] Depends on the amount of ambient drying occurs.

[12] Depends on the amount of litter or bedding used. Litter/bedding decreases moisture and bulk density dilutes nutrients and increases structure and degradability.

[13] Also, depends on methods of collection.

[14] Manure from outdoor feedlots includes soil that is incidentally collected with the manure. Soil increases the bulk density and ash content.

[15] Some manures may contain noticeable amounts of copper due to the use of copper sulfate in footbaths.

[16] Typically occurs as a “bedded pack,” manure mixed with bedding that accumulates for months.

[17] Solids settled out from fish rearing ponds and raceways. May contain a fair amount of soil.

[18] Moisture and nutrient content depend on exposure to weather.

[19] Composting improves if chopped.

[20] Structure disappears quickly, after plant cells begins to decompose and release moisture.

[21] Residue remaining after juice is pressed out. May include pressing and filtering aides like diatomaceous earth. Grape pomace includes seeds that resist decomposition.

[22] Highly variable, depending on the source and presence of other items, especially paper and cardboard.

[23] May be highly contaminated with plastic if not separated at the source.

[24] Highly variable depending on the product and processes.

[25] Primary value is as a source of moisture.

[26] May contain bones.

[27] Fish waste ground into a liquid slurry.

[28] E.g., lobster and crab shells decompose during composting.

[29] E.g., clam, mussel, and scallop shells. Attached meat decomposes during composting but the shells remain intact.

[30] May have other higher value uses compared to composting.

[31] Stomach content of cattle and other ruminant animals at the time of slaughter. Silage-lake in consistency.

References

Cited references

Amlinger, F., Line Diana Blytt, L.D., 2013. How to Comply with the EU Animal By-Products Regulations at Composing and Anaerobic Digestion Plants. European Compost Network. https://www.compostnetwork.info/download/good-practice-guide-comply-eu-animal-products-regulations-composting-anaerobic-digestion-plants/.

Arikan, O.A., Sikora, L.J., Mulbry, W., Khan, S.U., Foster, G.D., 2007. Composting rapidly reduces levels of extractable oxytetracycline in manure from therapeutically treated beef calves. Bioresour. Technol. 98, 169–176.

Arikan, O.A., Mulbry, W., Rice, C., 2009. Management of antibiotic residues from agricultural sources: use of composting to reduce chlortetracycline residues in beef manure from treated animals. J. Hazard Mater. 164 (2–3), 483–489.

Balch, A., Wilkinson, K., Schliebs, D., Hazell, L., 2019. Critical Evaluation of Composting Operations and Feedstock Suitability Critical Evaluation of Composting Operations and Feedstock Suitability, Phase 1 Report – Odour Issues. Arcadis Australia Pacific Pty Limited prepared for the Department of Environment and Science (DES Queensland). https://environment.des.qld.gov.au/__data/assets/pdf_file/0024/226293/phase-1-composting-study-report.pdf.

Beecher, N., Brown, S., 2018. PFAS and Organic Residuals Management, Parts I and II. BioCycle. July and August 2018.

Brinton, W., Dietz, C., Bouyounan, A., Matsch, D., 2018. Microplastics in compost: the environmental hazards inherent in the composting of plastic-coated paper products. Woods End Lab. and Eco-cycle. http://ecocycle.org/files/pdfs/microplastics_in_compost_summary.pdf.

BPI (Biodegradable Plastics Institute), 2020. The Compostable Logo. https://bpiworld.org/BPI-Public/Program.html/.

Buyuksonmez, F., Rynk, R., Hess, T.F., Bechinski, E., 1999. Occurrence, degradation and fate of pesticides during composting: Part I: composting, pesticides, and pesticide degradation. Compost Sci. Util. 7 (4), 66–82.

Buyuksonmez, F., Rynk, R., Hess, T.F., Bechinski, E., 2000. Occurrence, degradation and fate of pesticides during composting: Part II: occurrence and fate of pesticides in compost and composting systems. Compost Sci. Util. 8 (1), 61–68.

Calisti, R., Regni, L., Proietti, P., 2020. Compost-recipe: a new calculation model and a novel software tool to make the composting mixture. J. Clean. Prod. 270 (10), 122427. https://doi.org/10.1016/j.jclepro.2020.122427. ISSN 0959-6526.

Camps, M., Tomlinson, T., 2015. The use of biochar in composting. Int. Biochar. Initiat. https://www.biochar-international.org/wp-content/uploads/2018/04/Compost_biochar_IBI_final.pdf.

Cataldo, E., Salvi, L., Paoli, F., Fucile, M., Masciandaro, G., Manzi, D., Masini, C.M., Mattii, G.B., 2021. Application of zeolites in agriculture and other potential uses: a review. Agronomy 11 (8), 1547. https://doi.org/10.3390/agronomy11081547.

Chandler, J.A., Jewell, W.J., Gossett, J.M., Van Soest, P.J., Robertson, J.B., 1980. Predicting methane fermentation biodegradability. In: Biotechnology and Bioengineering Symposium No. 10, pp. 93–107.

Chen, Z., Zhao, W., Xing, R., Xie, S., Yang, X., Cui, P., Lü, J., Liao, H., Yu, Z., Wang, S., Zhou, S., 2020. Enhanced in situ biodegradation of microplastics in sewage sludge using hyperthermophilic composting technology. J. Hazard Mater. 384 (2020), 121271. https://doi.org/10.1016/j.jhazmat.2019.121271. ISSN 0304-3894.

Coker, C., 2020a. Managing PFAS chemicals in composting and anaerobic digestion. Biocycle. January 21 and 28, 2020.

Dolliver, H., Gupta, S., Noll, S., 2008. Antibiotic degradation during manure composting. J. Environ. Qual. 37, 1245−1253.

Donoho, A.L., 1984. Biochemical studies on the fate of monensin in animals and the environment. J. Anim. Sci. 58 (6), 1528−1539.

EEA (European Environment Agency), 2020. Biodegradable and Compostable Plastics Challenges and Opportunities. https://doi.org/10.2800/552241. ISBN 978-92-9480-257-6 ISSN 2467-3196. https://www.eea.europa.eu/publications/biodegradable-and-compostable-plastics.

Ekinci, K., Keener, H.M., Elwell, D.L., 2000. Composting short paper fiber with broiler litter and additives: part i: effects of initial pH and carbon/nitrogen ratio on ammonia emission. Compost Sci. Util. 8 (2), 160−172. https://doi.org/10.1080/1065657X.2000.10701761.

EFSA J. 18 (8), 2020, 6226. https://www.efsa.europa.eu/en/efsajournal/pub/6226.

Frischmann, C., 2018. The climate change impact of food in the back of your fridge. Wash. Post. July 341, 2018.

Gouleke, C.G., 1972. Composting: A Study of the Process and its Principles. Rodale Press, Inc, Emmaus, PA.

Khan, S.J., Roser, D.J., Davies, C.M., Peters, G.M., Stuetz, R.M., Tucker, R., Ashbolt, N.J., 2008. Chemical contaminants in feedlot wastes: concentrations, effects and attenuation. Environ. Int. 34, 839−859.

Kayhanian, M., Tchobanoglous, G., 1992. Computation of C/N ratios for various organic fractions. Biocycle 33 (5), 58−60.

Lemmon, C.R., Pylypiw, H.M., 1992. Degradation of diazinon, chlorpyrifos, isofenphos and pendimethalin in grass and compost. Bull. Environ. Contam. Toxicol. 48 (3), 409−415.

McKellar, Q.A., 1997. Ecotoxicology and residues of anthelmintic compounds. Vet. Parasitol. 72, 413−435.

Oshins, C., 2019. Bulk Density and FAS Measurement. CCREF Compost Operators Training Workbook, Ithaca, NY. August 2019. https://www.compostfoundation.org/Education/COTC.

Paul, J., Geesing, D., 2015. Compost Facility Operator Manual. Transform Compost Systems, Abbotsford, BC. http://www.transformcompostsystems.com/learn-compost-operator-manual.php.

Pauwels, B., Wille, K., Noppe, H., De Brabander, H., Van de Wiele, T., Verstraete, W., Boon, N., 2008. 17α-ethinylestradiol cometabolism by bacteria degrading estrone, 17β-estradiol and estriol. Biodegradation 19, 683−693.

Puglisi, E., Cappa, F., Fragoulis, G., Trevisan, M., Del Re, A.A.M., 2007. Bioavailability and degradation of phenanthrene in compost amended soils. Chemosphere 67, 548−556.

Puyuelo, B., Ponsá, S., Gea, T., Sánchez, A., 2011. Determining C/N ratios for typical organic wastes using biodegradable fractions. Chemosphere 85 (4), 653−659. https://doi.org/10.1016/j.chemosphere.2011.07.014. ISSN 0045-6535.

Richard, T., 1996. The Effect of Lignin on Biodegradability. Cornell Waste Management Institute. http://compost.css.cornell.edu/calc/lignin.html.

Sanchez-Monedero, M.A., Cayuela, M.L., Roig, A., Jindo, K., Mondini, C., Bolan, N., 2018. Role of biochar as an additive in organic waste composting. Bioresour. Technol. 247, 1155–1164. https://doi.org/10.1016/j.biortech.2017.09.193. PMID: 29054556.

Soares, M.A., Quina, M.J., Quinta-Ferreira, R., 2013. Prediction of free air space in initial composting mixtures by a statistical design approach. J. Environ Manage. 128, 75–82. https://doi.org/10.1016/j.jenvman.2013.04.041. Epub 2013 May 27. PMID: 23722176.

Soudejania, H.T., Kazemian, H., Inglezakis, V.J., Zorpase, A.A., 2019. Application of zeolites in organic waste composting: A review. Biocatalysis and Agricultural Biotechnology 22, 101396.

Storteboom, H.N., Kim, S.-C., Doesken, K.C., Carlson, K.H., David, J.G., Pruden, A., 2007. Response of antibiotics and resistance genes to high-intensity and low-intensity manure management. J. Environ. Qual. 36, 1695–1703.

Strom, P.F., 2000. Pesticides in yard waste compost. Compost Sci. Util. 8 (1), 54–60.

Tchobanoglous, G., Theisen, H., Vigil, S.A., 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw-Hill, New York, NY.

USCC, 2020. PFAS in Compost. https://www.compostingcouncil.org/page/pfas.

Van den Oever, M., Molenveld, K., Van der Zee, M., Bos, H., 2017. Bio-based and biodegradable plastics - facts and figures. Wageningen Food Biobased Res. 172. ISBN-number 978-94-6343-121-7. https://doi.org/10.18174/408350.

Vandervoot, C., Zabik, M.J., Branham, B., Lickfeldt, D.W., 1997. Fate of selected pesticides applied to turfgrass: effect of composting on residues. Bull. Environ. Contam. Toxicol. 58, 38–45.

Wang, S.P., Zhong, X.Z., Wang, T.T., Sun, Z.-Y., Tang, Y.Q., Kida, K., 2017. Aerobic composting of distilled grain waste eluted from a Chinese spirit-making process: the effects of initial pH adjustment. Bioresour. Technol. 245 (Pt A), 778–785. https://doi.org/10.1016/j.biortech.2017.09.051.

Watteau, F., Dignac, M., Bouchard, A., Revallier, A., Houot, S., December 11, 2018. Microplastic detection in soil amended with municipal solid waste composts as revealed by transmission electronic microscopy and pyrolysis/GC/MS. Front. Sustain. Food Syst. https://doi.org/10.3389/fsufs.2018.00081.

Weithmann, N., Möller, J.N., Löder, M.G.J., Piehl, S., Laforsch, C., Freitag, R., 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Sci. Adv. (published online April 4, 2018) https://advances.sciencemag.org/content/4/4/eaap8060.

Consulted and suggested reading

Aikaitė-Stanaitienė, J., Grigiškis, S., Levišauskas, D., Čipinytė, V., Baškys, E., Kačkytė, V., 2010. Development of fatty waste composting technology using bacterial preparation with lipolytic activity. J. Environ. Eng. Landscape Manag. 18 (4), 296–305.

Allison, F.E., 1965. Decomposition of wood and bark sawdusts in soil, nitrogen requirements, and effects on plants. Agric. Res. Serv. USDA, Tech. Bull. No. 1332.

Awasthi, M.K., Wang, Q., Ren, X., Zhao, J., Hui Huan, H., Awasthi, S.K., Lahori, A.H., Li, R., Zhou, L., Zhang, Z., November 2016. Role of biochar amendment in mitigation of nitrogen loss and greenhouse gas emission during sewage sludge composting. Bioresour. Technol. 219, 270–280.

Barthod, J., Rumpel, C., Dignac, M., 2018. Composting with additives to improve organic amendments. A review. Agron. Sustain. Dev. 38. Article number:17.

Bayard, R., Benbelkacem, H., Gourdon, R., Buffière, P., June 15, 2018. Characterization of selected municipal solid waste components to estimate their biodegradability. J. Environ. Manag. 216, 4–12.

Bekier, J., Drozd, J., Jamroz, E., Jarosz, B., Kocowicz, A., Walenczak, K., Weber, J., 2013. Changes in selected hydrophobic components during composting of municipal solid wastes. J. Soils Sediments 2014 (14), 305–311. https://doi.org/10.1007/s11368-013-0696-0.

California Organics Recycling Council, 2011. Compostable Plastics 101. Available from: USCC Compostable Plastics Tollkit: https://www.cptoolkit.org/Portals/0/Documents/Compostable%20Plastics%20101%20Paper.pdf.

Chai, E.W., H'ng, P.S., Peng, S.H., Wan-Azha, W.M., Chin, K.L., Chow, M.J., Wong, W.Z., 2013. Compost feedstock characteristics and ratio modelling for organic waste materials co-composting in Malaysia. Environ. Technol. 34 (17–20), 2859–2866. https://doi.org/10.1080/09593330.2013.795988.

Cogger, C., Bary, A., Sullivan, D.M., 2002. Fertilizing with yard trimmings. WSU Bull.

Coker, C., January 21, 2020a. Managing PFAS chemicals in composting and anaerobic digestion. Biocycle. https://www.biocycle.net/managing-pfas-chemicals-composting-anaerobic-digestion/.

Coker, C., January 28, 2020b. Managing Treatment of PFAS-contaminated composting site runoff. Biocycle. https://www.biocycle.net/treatment-pfas-contaminated-composting-site-runoff/.

Esan, E.O., Abbey, L., Yurgel, S., March 25, 2019. Exploring the long-term effect of plastic on compost microbiome. PLoS One. https://doi.org/10.1371/journal.pone.0214376.

Evanylo, G.K., Sherony, C.A., May, J.H., Simpson, T.W., Christian, A.H., 2009. The Virginia Yard-Waste Management Manual, second ed. Virginia Cooperative Extension https://vtechworks.lib.vt.edu/bitstream/handle/10919/48325/452-055_pdf.pdf?sequence=1&isAllowed=y.

Food and Fertilizer Technology Center for the Asian and Pacific Region, 2005. Raw Materials Used for Composting. https://www.fftc.org.tw/en/publications/detail/1442.

Godley, A., Lewin, K., Graham, A., Barker, H., Smith, R., 2004. Biodegradability determination of municipal waste: an evaluation of methods. In: Proc. Waste 2004 Conf. Integrated Waste Management and Pollution Control: Policy and Practice, Research and Solutions. Stratford-upon-Avon, UK, 28-30 September 2004, pp. 40–49.

Godlewska, P., Schmidt, H.P., Ok, Y., Oleszczuk, P., 2017. Biochar for composting improvement and contaminants reduction: a review. Bioresour. Technol. 246, 193–202.

Guzman, A., Gnutek, N., Janik, H., 2011. Biodegradable polymers for food packaging - factors influencing their degradation and certification types a comprehensive review. Chem. Chem. Technol. 5, 115–122.

Hagemann, N., Subdiaga, N., Orsetti, S., de la Rosa, J.M., Knicker, H., Schmidt, H.P., Kappler, A., Behrens, S., February 1, 2018. Effect of biochar amendment on compost organic matter composition following aerobic composting of manure. Science Direct Sci. Total Environ. 613–614, 20–29.

Han, W., Clarke, W., Pratt, S., 2014. Composting of waste algae: a review. Waste Manag. 34 (7), 1148–1155.

Hills, K., 2019. The Devil Is in the Process: Co-composting Biochar Could Benefit Crop Growth and the Environment. CSANR.

Keener, H., Wicks, M., Michel, F., Ekici, K., 2014. Composting Broiler Litter. Cambridge Core 70 (4). Cambridge University Press.

Kissinger, W.F., Koelsch, R.K., Erickson, G.E., Klopfenstein, T.J., May 2007. Characteristics of manure harvested from beef cattle feedlots. Biol. Syst. Eng. Papers Pub 23 (3), 357–365. University of Nebraska.

Krishna, M.P., Mohan, M., 2017. Litter decomposition in forest ecosystems: a review. Energy Ecol. Environ. 2, 236–249. https://doi.org/10.1007/s40974-017-0064-9.

Krogmann, U., Westendorf, M.L., Rogers, B.F., 2006. Best Management Practices for Horse Manure Composting on Small Farms. Rutgers Cooperative Research & Extension, Bulletin, p. E307.

Lemus, G.R., Lau, A.K., 2002. Biodegradation of lipidic compounds in synthetic food wastes during composting. Can. Biosyst. Eng. 44, 2002.

Magri, A., Teira-Esmatges, M.R., 2015. Assessment of a composting process for the treatment of beef cattle manure. J. Environ.l Sci. Health Part B Pestic. Food Contam. Agric. Wastes 50 (6).

Manitoba Agriculture, Food and Rural Development, 2015. Properties of Manure. agrienv@gov.mb.ca.manitoba.ca/agriculture.

Massachusetts Department of Environmental Protection, 2003. Supermarket Composting Handbook. https://www.mass.gov/files/documents/2016/08/ql/smhandbk.pdf.

Mason, G., 2009. Predicting biodegradable volatile solids degradation profiles in the composting process. Waste Manag. 29 (2), 559–569. https://doi.org/10.1016/j.wasman.2008.05.001. Epub 2008 Jun 24.

Mercer, W.A., Rose, W.W., Champan, J.E., Katsuyama, A., 1962. Aerobic composting of vegetable and fruit wastes. Compost. Sci. 3-3, 9–19.

Mercer, W.A., Rose, W.W., 1968. Windrow composting of fruit waste solid. Compost. Sci. 9–3, 19–22.

Nakasaki, K., Nagasaki, K., Ariga, O., 2004. Degradation of fats during thermophilic composting of organic waste. Waste Manag. Res. 22 (4), 276–282. https://doi.org/10.1177/0734242X04045430.

Niladri, P., Utpal, G., Gourab, R., 2019. Composting. In: Larramendy, M., Soloneski, S. (Eds.), Organic Fertilizers - History, Production and Applications. IntechOpen. https://doi.org/10.5772/intechopen.88753. Available from: https://www.intechopen.com/books/organic-fertilizers-history-production-and-applications/compostingComposting.

Northup, B.K., Zitzer, S.F., Archer, S., McMurtry, C.R., Boutton, T.W., 2004. Above-ground biomass and carbon and nitrogen content of woody species in a subtropical thornscrub parkland. J. Arid Environ. 62 (2005), 23–43.

Pan, Y., Farmahini-Farahani, M., O'Hearn, P., Xiao, H., Ocampo, H., 2016. An overview of bio-based polymers for packaging materials. J. Bioresour. Bioprod. 1 (3), 106–113. https://doi.org/10.21967/jbb.v1i3.49.

Reid, I., 2011. Biodegradation of lignin. 2011·. Can. J. Bot. 73 (S1), 1011–1018. https://doi.org/10.1139/b95-351.

Ricci-Jürgensen, M., Gilbert, J., Ramola, A., 2020. Global Assessment of Municipal Organic Waste Production and Recycling. International Solid Waste Association. https://www.iswa.org/uploads/media/Report_1_Global_Assessment_of_Municipal_Organic_Waste_Compressed_v2.pdf.

Richard, C., 2013. Evaluation of Waste Gypsum Wallboard as a Compost Additive. Thesis. Dalhousie University, Halifax, Nova Scotia.

Rose, W.W., Katsuyama, A., Chapman, J.E., Porter, V., Roseid, S., Mercer, W.A., 1965. Composting fruit and vegetable refuse. Compost Sci 6–2, 13–25.

Scott, G.M., Smith, A., 1995. Sludge characteristics and disposal alternatives for the pulp and paper industry. In: Proceedings of the 1995 International Environmental Conference; Atlanta, GA. Atlanta, GA: Tappi Press: 269-279; 1995.

Taylor, J., Warnken, M., 2008. Wood Recovery and Recycling: A Source Book for Australia. Forest and Wood Products Australia, Melbourne. https://www.fwpa.com.au/images/marketaccess/PNA017-0708_Wood_Recycling_0.pdf.

Tuomela, M., Vikman, M., Hatakka, A., Itävaara, M., 2000. Biodegradation of lignin in a compost environment: a review. Sci. Direct Bioresour. Technol. 72 (2), 169–183.

Valzano, F., Western Sydney Waste Board, University of New South Wales., Recycled Organics Unit., 2000. A Literature Review on the Composting of Composite Wood Products Draft. University of New South Wales Resource Organics Unit, Sydney.

van der Linden, A., Reichel, A., 2020. Bio-waste in Europe — turning challenges into opportunities. Eur. Environ. Agency Rep. No 04/2020.

Van der Zee, M., Molenveld, K., June 2, 2020a. Fate of compostable products during industrial composting of SSO. Biocycle.

Van der Zee, M., Molenveld, K., June 15, 2020b. Compostable product disintegration rate. Biocycle.

Van Gestel, K., Mergaert, J., Swings, J., Coosemans, J., Ryckeboe, J., 2003. Bioremediation of diesel oil-contaminated soil by composting with biowaste. Environ. Pollut. 125 (3), 361–368.

Vandecasteele, B., Sinicco, T., D'Hose, D., Vanden Nest, T., Mondini, C., March 1, 2016. Biochar amendment before or after composting affects compost quality and N losses, but not P plant uptake. J. Environ. Manag. 168, 200–209.

Vidussi, F., Rynk, R., 2001. Meat by products as composting feedstocks, Parts 1 and 2. Biocycle. January and March 2001.

Walters, R., 2020. Composting basics: C:N ratio and recipe making. Technical Note 25. Dirt Hog's Compan.

Wang, X., Zhao, Y., Wang, H., Zhao, X., Cui, H., Wei, Z., 2017. Reducing nitrogen loss and phytotoxicity during beer vinasse composting with biochar addition. Waste Manag. 61, 150–156.