Technical Note 24.

Composting Basics: Bulk Density, Moisture, Porosity

24.0 Background

Compositing has come a long way since the days of Sir Albert Howard and the Indore experiments. Once an arcane, if faintly untoward, practice of organic farmers and gardeners, composting has evolved to a full-fledged science with built-in engineering controls that make the composting process predictable and much more efficient. Material properties like bulk density, moisture, and porosity influence microbial decomposition of waste material in compost. Knowledge of the optimal conditions for microbial decomposition ensures efficient bioconversion of waste products so that they can be beneficially and safely used as fertilizer and soil conditioners.

Bulk density refers to ratio of the total weight (mass) of compost to its volume. Common units of measure are pounds per cubic yard (lb/yd^3, English units) or kilograms per cubic meter (kg/m^3, metric units). Bulk density is needed to convert compost recipes from weight to a volume basis for field mixing. Bulk density directly affects the transportation and storage of compost. The amount of moisture in compost strongly affects bulk density, with wetter materials having a higher bulk density compared to dry materials. As such, bulk density of compost is always calculated on a wet basis. In contrast, soil bulk density ("compaction") is calculated on a dry basis, i.e. the amount of water in soil does not affect its measured bulk density. The optimal compost bulk density range is 800-1,200 lb/yd^3.

Adequate moisture is needed for microbial respiration that is responsible for the decomposition of waste material in compost. Too little water will deactivate microorganisms, whereas too much water favors anaerobic microbes that produce fermentation. Anaerobic conditions slow decomposition and may produce bad odors, noxious gases and phytotoxic acids, lowering the quality of compost. Moisture content between 40-60% is ideal for compost under aerobic conditions.

Porosity refers to the amount of air-filled pore space in compost that is not occupied by solid particles or water. Porosity is expressed as a percentage of the total bulk volume of the compost pile. An adequate supply of oxygen is needed for microbial respiration in aerobic decomposition. Aeration provides oxygen and stimulates the removal of heat, water vapor, and gases during the active composting phase. The normal level of oxygen in the atmosphere is 21%. A minimum of 5% oxygen is needed in the compost pile to keep aerobic microorganisms alive. This minimal level is met when the air-filled pore space in the pile is above 20%. Adding too much air will slow composting due to excessive drying and/or low temperatures in the pile. An optimal air-solid balance is achieved when the free air space (porosity) in the pile is in the 35-60% range.

This technical note explains how to determine bulk density, moisture, and porosity of compost and compost material.

24.1 Determining Bulk Density and Porosity

Typically, bulk density and porosity are determined for a compost *ingredient*, i.e. the starting material for compost. The resulting information is then used to find the optimal field mixing ratio of the raw ingredients for composting. This is most efficiently done using spreadsheets designed for calculating optimal mixing ratios. Several spreadsheets are publicly available via the internet, see section 24.3 for source URLs. Mixing spreadsheets often include published values for "average" bulk density of common composting ingredients. Other relevant material properties like moisture, nitrogen, and carbon content, and C:N ratio also may be included in the spreadsheet.

Why, then, should we determine compost material properties that are available in spreadsheets? First, there are many possible ingredients and combinations of ingredients used for composting. Not all of these have published values. Predetermined bulk density and moisture values are valid for ingredients with similar composition. When one or more ingredients in the compost changes its bulk density also changes. A novel ingredient must be tested analytically for nutrient content and C:N ratio, and its bulk density and moisture content determined on-site. By measuring material properties like porosity we become familiar with the level of aeration that is optimal for microbial respiration, and to better judge if a pile needs mixing to add air, or more particle mass to increase bulking and reduce moisture loss.

Mixing spreadsheets are usually "plug and play" format, i.e. the user inserts values in designated "input" cells and answers appear as if by magic, in "output" cells. All very well, Houdini, but transparency as to how the answers are derived vary by spreadsheet, and may be completely obscured by embedded macro programs. The following tutorial explains how bulk density and porosity can be accurately determined for prepared compost or for individual raw materials.

Note: bulk density and porosity and best determined in tandem. Equipment needed is:

- Tape measure and black marking pen
- Water
- 5-gallon plastic bucket, clean
- Scale, 0-50 pounds capacity hook or platform type preferred
- Hand-held calculator
- Compost or Ingredient sample

Procedure:

1. Measure the height of a 5-gallon bucket from its inner bottom to brim. Make a mark 1/3 and 2/3 down from the top brim fill level. If the bucket has a 5-gallon fill mark, use that as the brim fill level (some buckets do not

have a fill mark, see step #3).

2. Weigh the empty bucket, and record its weight (**W$_B$**).

3. Determine the effective volume of the bucket, which may vary significantly from its nominal 5-gallon capacity depending on manufacturer and model (Figure 1). Five gallon buckets have sloping sides designed for stacking. Three measurements are needed to compute the volume of a bucket with sloping sides: (1) bottom diameter (***d***); (2) brim diameter (***D***); and (3) height (***h***) measured from center bottom to brim (see Figures 2a, b, c). If you invert a 5-gallon bucket bottom end up, it turns into a geometric shape called a ***frustum*** (Figure 2d). A frustum is a cone with its top cut off. Its volume is computed as:

$$V = \frac{\pi h}{3}\left(R^2 + Rr + r^2\right)$$

where R is the radius of the lower base, equal to ½ the brim diameter ***D*** (***D***÷2); r is the radius of the upper base, equal to ½ the bottom diameter ***d*** (***d***÷2); and ***h*** is the height measured in step #1.

For example, measurements for the 5-gallon bucket shown in Figures 2a, b, c (EZ grip by Encore Plastics) are as follows:

D=$11\frac{5}{16}$ inches, or 0.943 feet (brim diameter)
d=10 inches, or 0.833 feet (bottom diameter)
h=14 inches, or 1.17 feet (inside height)

Note that we convert inches and fractions of an inch to feet because we want the volume in cubic feet, not inches. The volume is given by:

$$V = \frac{\pi\ x\ 1.17}{3}\left(0.472^2 + (0.472\ x\ 0.416) + 0.416^2\right)$$

$$V = 0.723\ cubic\ feet$$

Some spreadsheets use the number 40 as a scaling factor in converting from cubic feet to cubic yards. This is based on the fact that 5 gallons of water occupies a volume of 0.668 cubic feet (1 gallon = 0.1337 cubic foot). Thus 5 gallons is 1/40th of one cubic yard. There are 27 cubic feet in one cubic yard, therefore 27 ÷ 0.668 ≈ 40. This obviates the need to calculate a bucket volume but it may introduce significant error as we shall see later on. Now back to bulk density...

4. Calculate the weight of water needed to fill the bucket to its brim (**W$_{H20}$**). For the EZ grip bucket, **W$_{H20}$** = 45.1 pounds (1 cubic foot of water weighs 62.37 pounds x 0.723 cubic feet). If your bucket has a fill line marking 5 gallons, **W$_{H20}$** = 41.7 pounds.

5. Fill the bucket 1/3rd full with material to be analyzed.

6. Raise the bucket to a height of 6 inches above a firm flat surface and let it drop 10 times.

7. Add additional material and fill to the 2/3rd full marker.

8. Repeat step #6 a **second time**, dropping the bucket 10 times from 6 inches.

9. Add material to the bucket and fill to the top brim.

10. Repeat the dropping procedure in step #6 a **third time**. After the third time, add material to the bucket and level off with the top brim. Do **not** repeat the dropping procedure in step #6.

Figure 1. Two "5-gallon" buckets from the same manufacturer but with different brim capacities. Where's the 5-gallon mark?

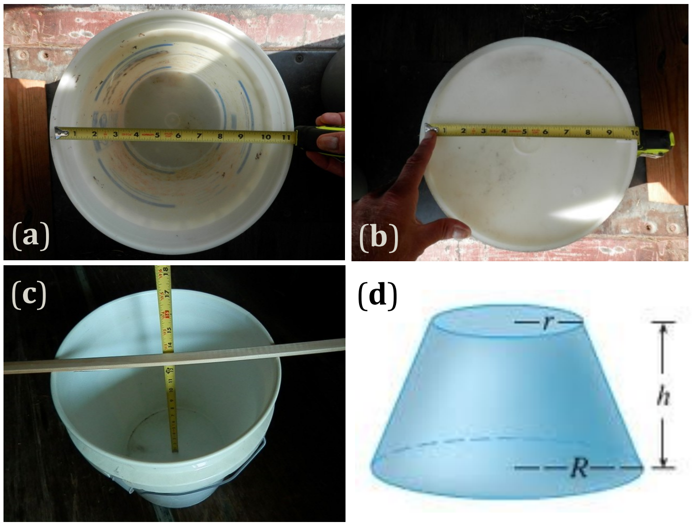

Figure 2. Three measurements are need to calculate the volume of a 5-gallon bucket: (**a**) brim diameter; (**b**) bottom diameter; and (**c**) height. Buckets with sloping sides are frustums (**d**), a cone with its top cut off.

11. Record the weight of the bucket and material (**W$_{B,M}$**) as accurately as is possible on the scale.

12. Fill pore space in the bucket by adding water to material to the bucket top brim.

13. Weigh bucket, material, and water (**W$_{B,M,\ H20}$**).[1]

14. Calculate bulk density (*BD*):

$$BD = \frac{1,686\ lb\ H_2O}{yd^3} \times \frac{W_{B,M} - W_B}{W_{H20}}$$

[1] Note that **W$_{B,M,H20}$** is *not* equivalent to **W$_B$+W$_M$+W$_{H20}$** according to steps 9-11.

Exercise: Calculate bulk density (*BD*) given the following:

Ingredient *a*

Weight of the bucket $\mathbf{W_B}$ = 2.0 lb.
Weight of the bucket and material $\mathbf{W_{B,M}}$=20.5 lb.
Weight of water in bucket $\mathbf{W_{H20}}$=45.1 lbs.
Weight of bucket, material, water $\mathbf{W_{B,M,H20}}$ =42 lb.

Ingredient *b*

Weight of bucket and material $\mathbf{W_{B,M}}$=32 lb.
Weight of bucket, material, water $\mathbf{W_{B,M,H20}}$ =50 lb.

Solution:

$$BD"a" = \frac{1{,}686\ lb\ \mathrm{H_2O}}{yd^3} \times \frac{20.5\ lb - 2.0\ lb}{45.1\ lb\ \mathrm{H_2O}}$$

$$BD,\ ingredient\ a = \frac{692\ lb}{yd^3}$$

$$BD"b" = \frac{1{,}686\ lb\ \mathrm{H_2O}}{yd^3} \times \frac{32.0\ lb - 2.0\ lb}{45.1\ lb\ \mathrm{H_2O}}$$

$$BD,\ ingredient\ b = \frac{1{,}122\ lb}{yd^3}$$

Ingredient *a* is outside the target 800-1,200 lb/yd^3 bulk density range. To remedy this, different volumes of ingredients *a* and *b* may be combined to achieve a blend with a more favorable bulk density. This is where mixing spreadsheets come in handy. They can formulate a compost recipe for any number of ingredients given bulk density, moisture content, and C:N ratio for each ingredient, resulting in an optimal "engineered" compost mix[2].

Average bulk density is calculated by dividing the sum of the weights of ingredients (lb) by the sum of their mix volumes (ft^3). In the example above, the weight of 10 cubic yards of ingredient *a* is:

$$10\ yd^3 \times \frac{692\ lb}{yd^3} = 6{,}920\ lb$$

The weight of 20 cubic yards of ingredient *b* is:

$$20\ yd^3 \times \frac{1{,}122\ lb}{yd^3} = 22{,}440\ lb$$

The sum of the weights of ingredients *a* and *b* is 22,440+6,920=29,360 pounds, and the sum of the their volumes is 10+20=30 cubic yards. Average bulk density is: calculated as:

$$\frac{sum\ of\ ingredient\ weights}{sum\ ingredient\ of\ volumes} = \frac{29{,}360\ lb}{30yd^3} = \frac{979\ lb}{yd^3}$$

Now the bulk density falls within the 800-1,200 lb/yd^3 range.

Calculate the air-filled pore space (AFPS, "porosity") as follows:

a. Calculate the weight of water in the pore space: Ingredient *a*: $\mathbf{W_{B,M,\ H20}}$ - $\mathbf{W_{B,M}}$ = 42 - 20.5 = 21.5 lb.
   Ingredient *b*: $\mathbf{W_{B,M,\ H20}}$ - $\mathbf{W_{B,M}}$ = 50—30 = 20 lb.
b. Calculate the AFPS:

$$AFPS = \frac{\mathrm{W_{B,M,H_2O}} - \mathrm{W_{B,M}}}{\mathrm{W_{H_2O}}}$$

$$AFPS,\ ingredient\ a = \frac{42\ lb - 20.5\ lb}{45.1\ lb} \times 100$$

$$AFPS,\ ingredient\ a = 48\%$$

$$AFPS,\ ingredient\ b = \frac{50\ lb - 30\ lb}{45.1\ lb} \times 100$$

$$AFPS,\ ingredient\ b = 44\%$$

Air-filled pore space of 48% and 44% is in the optimal 35-60% range so these materials can be mixed in any ratio or mixed with low porosity material for better aeration.

Earlier, we mentioned that generalized scaling factors used in spreadsheets for calculating bulk density may introduce error if the bucket volume varies. What happens if we use 40 as a scaling factor for *V*=0.668 cubic feet (given in some spreadsheets) instead of the calculated volume of our bucket *V*= 0.723 cubic feet? The bulk density is calculated as:

$$BD = \left(W_{B,M} - W_B\right) \times 40$$

$$BD,\ ingredient\ a = \left(20.5\ lb - 2.0\ lb\right) \times 40$$

$$BD,\ ingredient\ a = \frac{740\ lb}{yd^3}$$

$$BD,\ ingredient\ b = \left(32\ lb - 20\ lb\right) \times 40$$

$$BD,\ ingredient\ b = \frac{1{,}200\ lb}{yd^3}$$

Bulk density is overestimated by 48 and 78 pounds per cubic yard for ingredients *a* and *b*, respectively. When tons of compost are processed this difference will be magnified. For design and engineering purposes, it's always better to calculate bulk density accurately using a measured volume rather than generalized scaling factors. For small operators the difference may be negligible. Spreadsheets may also use scaling factors to calculate air-filled pore space. These are usually derived at by factoring the weight per gallon of water (8.34 lb/gal), and the volume it occupies in a 5-gallon bucket. The weight of water doesn't change, but as we have seen, the volume of a 5-gallon bucket may vary, sometimes significantly, so general AFPS scaling factors will also introduce error in calculation.

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[2] Carbon to nitrogen (C:N) ratio and moisture content are the most critical variables in composting. These values, when known, are factored into spreadsheet calculations. Water or nitrogen fertilizer may also be added to the final mix to achieve optimal % moisture and C:N ratio. See Technical Note 25 "Compost C:N Ratio and Recipe Making" for information on how to calculate compost moisture content and C:N ratio.

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24.2 DETERMINING MOISTURE CONTENT

There are two methods for moisture determination:

- The "squeeze" test
- Weighing a moist and dry sample

The squeeze test relies on qualitative estimation of moisture content by the way a handful of compost sample feels and behaves when squeezed firmly. Results are interpreted in one of the following ways:

1. If the squeezed material crumbles and does not stick together, and your hand feels dry, the material is about 40% moisture or less.
2. If the squeezed material sticks together, and your hand feels moist, the material is about 50% moisture.
3. If the squeezed material sticks together and drips, and your hand is wet, the material is above 60% moisture.

With practice, it is possible to estimate moisture content consistently to within 5% in the optimal range.

Weighing a moist and dry sample relies on quantitative evaporation of moisture via heat or microwave energy. The microwave method requires the following equipment:

- Weigh scale (top loading or triple-beam)
- Microwave oven
- Paper plates, disposable

Procedure:

1. Place the paper plate on the scale and adjust the scale so it reads zero ("tare").
2. Weigh out 100 units (grams, ounces etc.) of sample on the paper plate.
3. Place sample and paper plate in a microwave oven. Reduce power level to 50%. Cook the sample in the oven for about 4 minutes.
4. Remove sample and paper plate from the microwave and weigh. Record this weight.
5. Place sample and paper plate back in the microwave oven for two more minutes of heating.
6. Reweigh the sample.
7. Repeat steps 5 and 6 until the weight of the sample and plate does not change for two consecutive measurements. Record final weight.
8. Subtract the final weight from 100 (weight of the original sample). This is the weight of water lost by evaporation. Divide this weight by 100 (weight of the original sample) and multiple by 100 to get per cent moisture content.

   Example:

   Weight of original sample = 100 g
   Weight after drying (-) 48 g
   Weight of water evaporated = 52 g

   Per cent moisture is given by:

$$\frac{52\ g}{100\ g}\ x\ 100$$

$$= 0.52\ x\ 100 = 52\%$$

Average moisture content of a mixture of two or more ingredients is calculated in the same manner as bulk density, i.e. by dividing the sum of the weight of water in each ingredient (lb) by the sum of their fresh weights (lb). This value is usually calculated automatically in mixing spreadsheets provided the % moisture content of the ingredients is known.

If a microwave oven is unavailable, the sample can be placed in a pie tin (or equivalent) and heated over a low flame on a gas-fired camp stove or stovetop. Drying time can be determined by placing a shard of clear bottle glass over the sample, concave side down, and watching to see if water vapor condenses on the underside of the glass. If water vapor condenses on the glass, continue cooking till all water has evaporated. Alternatively, the moist sample can be air-dried over several days. The number of days it takes the sample to reach a constant weight will depend on temperature and humidity. Air-drying is less accurate because not all of the moisture may be evaporated from the sample. However, it's sufficient for operations where high accuracy isn't needed.

24.3 REFERENCES

Compost mix optimizers:

Cornell University: Department of Agricultural and Biological Engineering. https://ecommons.cornell.edu/handle/1813/44670 Developer: Tom Richard

Michigan State University: Department of Animal Science. https://www.canr.msu.edu/resources/spartan-compost-recipe-optimizer-v1-05 Developers: Dale Rozeboom and Robert Kriegel. Updated December 5, 2019.

Ohio State University: Department of Food, Agricultural and Biological Engineering. https://ocamm.osu.edu/composting Developer: Harold Keener. Note: English and metric versions of this spreadsheet are available.

Washington State University: Department of Crop and Soil Sciences. https://puyallup.wsu.edu/soils/compost-mix-calculator/ Developers: Andy Bary and Craig Cogger.

24.4 FURTHER READING

Carolinas Composting Council and Carolina Recycling Association. Yes You Can! (Compost and Naturescape) Train-the-Trainers Course. https://agrosphere-international.net/Documents/DHC/YesYouCAN-Carolina%20Composting%20Council(Train%20the%20Trainers).pdf

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