NCASI Briefing Note

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The Use of Paper and Paper Products in a Composting Environment

SEPTEMBER 2018

1.0 Introduction

Increasingly, users of paper and paper products are looking for alternative disposal options to the traditional practice of disposal in a landfill. While recycling remains the primary alternative, composting paper is often suggested as an alternative disposal option that can reduce reliance on landfills (NCASI 2005) and provide additional benefit through the production of a valuable soil amendment. Compared to landfilling and recycling, composting paper is still a relatively uncommon practice, although the rise in commercial and municipal composting operations has increased, creating more opportunities (NCASI 2005). Users often still raise questions related to the suitability of using paper as a compost feedstock and the potential environmental impacts of doing so.

General composting guidance typically supports the use of paper and paper products. Several national and local environmental organizations in North America, along with other gardening and composting authorities, often suggest composting paper is an acceptable practice. For instance, the USDA National Resource Conservation Service provides guidance for composting, in which they list materials that can be added to compost piles - shredded paper being one of the acceptable materials (NRCS 2018). The Ontario Ministry of Environment (MOECC) publishes similar guidance for composting in Ontario and lists acceptable feedstocks that include paper waste and soiled paper (MOECC 2016). The MOECC states that a preference in feedstock should be given to "certified compostable[1] items or paper products" over other manufactured materials. Other organizations, such as the Compost Council of Canada and the US Composting Council provide general recommendations for appropriate composting material, including paper (Compost Council of Canada 2010; US Composting Council 2009). In addition to use as a feedstock, the US Composting Council also recommends using waste paper to manage wet food wastes prior to adding to a compost pile. Other guidance documents found online or in gardening/soil textbooks (Brady and Weil 2008) often recommend the use of paper as a composting feedstock.

While there are general recommendations for composting paper, relatively little attention has been given in the scientific literature to the biodegradability and compostability of paper (Tuomela et al. 2000) and what impacts it may have on the final compost product. This review is a summary of some of the research that has been done to investigate the suitability of using paper and paper products in a composting environment. When possible, results have been separated based on product type (e.g. bleached, unbleached, and coated). This review provides further insight to the impacts, if any, of using paper products for composting.

[1] Certified Compostable – A product, package or bag that has been officially endorsed as compostable under a third party operated accredited certification program, in accordance with specified criteria.

2.0 Biodegradation of woody material in a soil environment

2.1 Carbon cycle

Before discussing paper composting, it is important to understand how wood biodegrades in nature. Composting is analogous to biodegradation of organic debris in soils (NCASI 2005) and as a wood-based product, paper follows similar biodegradation pathways to those of woody material. Degradation of wood is the reduction in molecular weight of complex molecules into simpler forms. In nature, and particularly in a soil environment, biodegradation through microbial activity is the dominant mechanism, with some deterioration occurring through physical stresses (Andrady et al. 1992). Biodegradation is a critical part of the carbon cycle, in which complex organic material is degraded into increasingly simpler forms until it can be used by microbes as a food source, converting the organic carbon back into CO_2 (Figure 1).

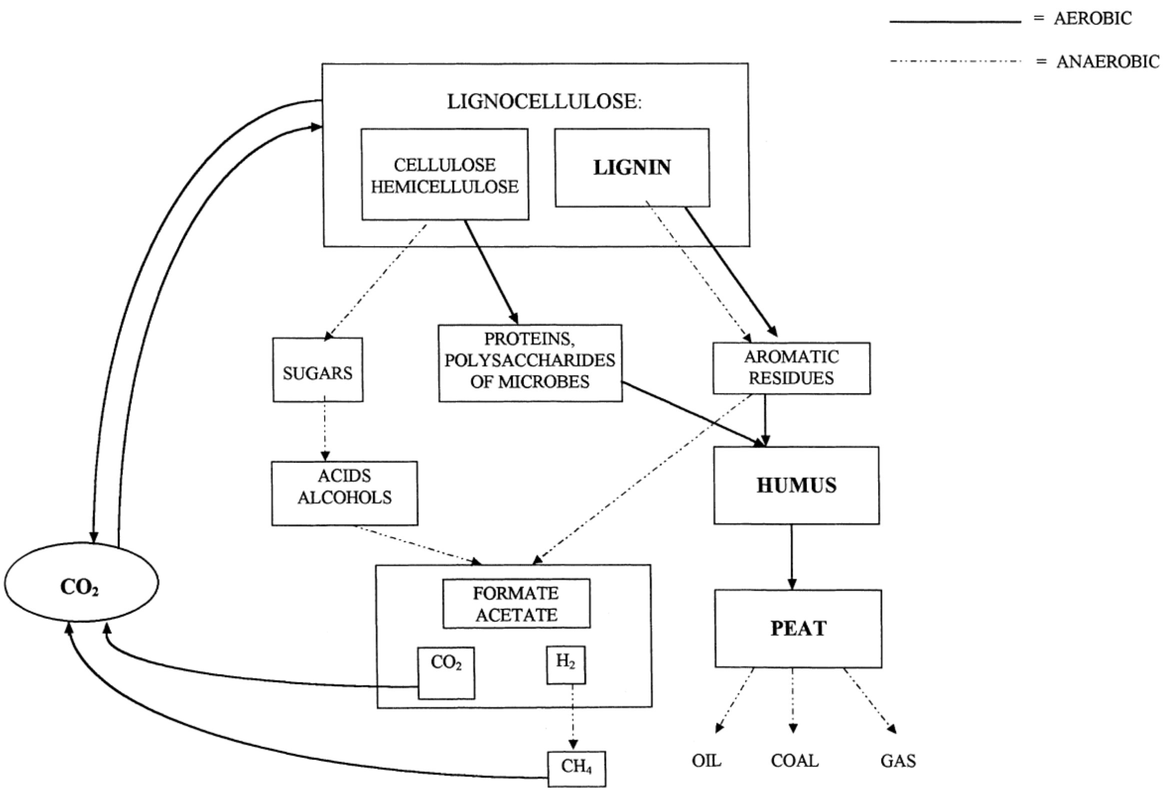

Figure 1 (Tuomela et al. 2000)

As shown in Figure 1, the main components of plant material are cellulose, hemicellulose, and lignin. These three components will vary based on plant species but typically make up a large percentage, with proteins, simple sugars and starches, fats and waxes, and polyphenols making up the rest (Brady and Weil 2008). Cellulose is composed of long chain polysaccharides consisting of linked beta-glucose molecules. As the principle component in cell walls, the long, rigid cellulose molecules provide strength to the cell wall (Raven et al. 1999). Hemicellulose is composed of varying polymeric structures made from five different sugar molecules that bind to both cellulose and lignin (Smook 2016). Lignin molecules are large, highly complex structures consisting mainly of interlinked phenolic rings (Brady and Weil 2008). The hemicellulose and lignin bind cellulose fibers together adding to the strength of woody plants.

2.2. Order of utilization
When dead woody material reaches the soil, microbial communities will utilize the simpler, easier-to-decompose compounds before attacking the more complex, resistant compounds. Typically, the more complex the substrate, the more extensive the enzyme system needed for utilization (Tuomela et al. 2000). The typical order of utilization is the following (Brady and Weil 2008; NCASI 1993):

1. sugars, starches, and simple proteins,
2. crude proteins,
3. hemicellulose,
4. cellulose,
5. fats and waxes, and
6. lignin.

As a long chain of glucose molecules, cellulose represents a large energy source for the microbial community, but the chemical bonds linking the sugar molecules are much harder to break apart than those in starch. To access the energy stored in cellulose, microbial organisms must first break down the glucose chain through the use of the extracellular enzyme cellulase (Brady and Weil 2008). Once broken down, the base sugars of cellulose and hemicellulose are readily metabolized to CO_2. This CO_2 is released back into the atmosphere where it can be taken in by plants and converted back into plant tissue via photosynthesis, completing the carbon cycle.

The complex structure of lignin makes it extremely resistant to attack by most organisms. After an extended period of time with some chemical modification, much of the lignin remains as soil humus. This soil humus is best characterized as a dark-colored, heterogenous, mostly colloidal mixture of modified lignin and newly synthesized organic compounds (Brady and Weil 2008). Soil humus is extremely recalcitrant, often storing carbon in the soil for extended periods of time, increasing the pool of stable soil organic matter.

3.0 Biodegradation in a compost environment

3.1 Composting fundamentals
Composting is the controlled biodegradation and transformation of organic material under primarily aerobic conditions producing CO_2, biomass, heat, and a humus-like organic material (Tuomela et al. 2000). The final compost product can be used to improve the growth of plants, enhance water holding and nutrient holding capacities of soil, increase soil aeration, and fight diseases (NCASI 2005). The biodegradation pathways during composting are similar to those discussed earlier in soil settings. The key difference being the process has been accelerated by providing optimal growth conditions for the microbial community (Brady and Weil 2008).

The composting process proceeds through three phases: mesophilic, thermophilic, and curing (Tuomela et al. 2000; Brady and Weil 2008). During the brief mesophilic phase microbes metabolize readily available food sources (e.g. sugars and starches) causing an increase in temperature. The thermophilic phase, lasting from weeks to months, occurs when temperatures rise between 40 and 75 °C. Cellulose decomposition occurs primarily during this time. The curing phase starts as most of the bioavailable carbon is consumed and microbial activity decreases represented by a decrease in temperature. The curing phase can last for several months.

3.2 Ideal composting conditions
Compost piles must be carefully maintained through each phase to ensure optimal conditions are present (Brady and Weil 2008; NCASI 1993). Table 1 is presented as general guidance for high-rate composting during the thermophilic phase and to highlight parameters that are of most importance. The values presented in Table 1 are not strict limits since optimal conditions will vary depending on feedstock, weather, composting method and quality requirements. Conditions during the mesophilic and curing stages will also have a different set of values, particularly for temperature and pH.

Table 1. Recommended Composting Conditions (NCASI 2005)

Parameter	Preferred Range	Reasonable Range
Moisture content (%)[a]	50 – 60	40 – 70
Carbon to nitrogen (C:N) ratio	25:1 – 30:1	20:1 – 40:1
Oxygen content (%)	>15	>5
pH	6.0 – 8.0	5.5 – 9.0
Porosity (%)	45 – 60	>40
Bulk density (lb/cu yd)	800 – 1000	700 – 1200
Particle size (diameter, inches)	0.5 – 2.0	Variable
Temperature (°C)	55 – 60	45 – 65

[a] Moisture content = ((wet weight of compost – oven dry weight of compost) / wet weight of compost) * 100

Maintaining an adequate moisture content is essential to the growing microbial community; however, it has been shown that periods of drying can actually increase biodegradation due to the burst of microbial activity after re-wetting (Brady and Weil 2008).

The C:N ratios listed in Table 1 are ideal to maintaining a growing microbial community. If high carbon feedstock is added increasing the C:N ratio, the pile will be nitrogen limiting, forcing bacteria to scavenge for nitrogen. This nitrogen limitation can inhibit growth and therefore reduce biodegradation of organic material until the C:N is brought back into ideal ranges. Compost piles with a low C:N ratio can leach excess nitrogen (Tuomela et al. 2000) or generate ammonia gas creating odor issues (NCASI 2005). Controlling feedstock inputs can help achieve ideal C:N ratios. Mixing in nitrogen-rich material (sewage sludge or manure) or high carbon material (paper, sawdust, leaves) to adjust a pile's C:N ratio is a proven strategy for balancing nutrients (Brady and Weil 2008).

While there are anaerobic bacteria and fungi that can metabolize cellulose and other organic compounds (NCASI 1993), biodegradation is much faster under aerobic conditions. It may be impossible to avoid generating anaerobic pockets within a pile, but those conditions can be minimized by maintaining a high overall oxygen concentration.

Reducing feedstock particle size before addition can help increase surface area, enhancing biodegradation (NCASI 2005; MOECC 2016). Shredding material can also ensure an even distribution of material throughout the pile. Generating particles that are too small, however, can cause compaction of the pile, decrease porosity, and reduce aeration.

Microbial activity increases with temperature. Higher temperatures, especially during the thermophilic phase, can be an indication of high microbial growth. Excessively high temperatures (>72 °C) can kill off mesophilic bacteria needed for degradation during the curing phase, and reduce biodegradation overall (NCASI 1993). Mixing can be used to cool piles reaching temperatures beyond the optimal range (NCASI 2005).

3.3 End product of composting

Similar to the natural soil environment, the final product from composting is a humus-like organic material derived mainly from lignin or other complex organic molecules found in the feedstock. This humic substance represents a large reservoir of organic carbon (Tuomela et al. 2000) and provides many of the benefits associated with compost such as high cation exchange capacity, increased water holding capacity, aggregate formation and soil stability, and reduced mobility of heavy metals (Brady and Weil 2008; NCASI 1993).

Bacteria such as actinomycetes can solubilize and modify lignin, but their ability to mineralize lignin is limited (Tuomela et al. 2000). Their modification of lignin during the thermophilic phase is particularly important for later degradation during the curing phase. Experiments have shown that composting with short thermophilic period resulted in lignin remaining undegraded even though total composting time was long (Tuomela et al. 2000).

While the humus is relatively stable, it can continue to decompose over time. In nature, white-rot fungus is the primary microbe responsible for lignin degradation. The slow degradation and mineralization of lignin can benefit perennial crops and forest by slowly releasing organically bound nitrogen into the soil (Brady and Weil 2008).

Adding too much lignin or not fully modifying the lignin during the thermophilic phase can impact overall degradation. Excessive amounts of lignin polymers can bind with cellulose fibers and other carbohydrates protecting them from microbial attack (Venelampi et al. 2003). High lignin feedstocks have also been shown to prevent anaerobic degradation of cellulose (Micales and Skog 1997)

4.0 Biodegradation of paper in compost environment

4.1 Paper (general)

In North America paper is made almost exclusively from wood fibers (Smook 2016). Fibers in the wood matrix are separated during mechanical or chemical pulping and then later recombined into a thin mat of fibers forming a sheet of paper. During mechanical pulping the lignin is softened through compression and friction, eventually freeing the cellulose fibers. For chemical pulping the objective is to dissolve lignin along with other soluble compounds (sugars, proteins, simple carbohydrates, etc.) and then separate them from the cellulose fibers. The resulting paper product is then primarily composed of cellulose fibers.

As a wood-based product, the biodegradation of paper follows a similar path to that of wood in a natural soil environment, with microbial communities enzymatically metabolizing wood fibers. The primary difference is that the physical and chemical processes during pulping can enhance microbial accessibility to these fibers (Andrady et al. 1992). These biodegradation enhancements are the result of an increased fiber surface area, when compared to wood, and by the breakdown and removal of lignin. Evidence of this enhancement in biodegradation can be seen when exposing paperboard to a biotic environment (even for short durations) through the simultaneous increase in CO_2 production and decrease in cellulose mass (Andrady et al. 1992).

Even with the increase in fiber availability in paper, microbial mineralization of cellulose fibers is still a relatively slow process compared to more readily available carbon sources such as those found in food scraps. The rate of cellulose degradation has been identified as the limiting factor in some composting operations (NCASI 1993). Therefore, it is important when composting paper products to maintain ideal conditions for microbial activity and provide sufficient time (12-15 weeks) for complete biodegradation of the cellulose fibers.

Paper is often high in carbon and lacking any significant amount of nitrogen, giving it a very high C:N ratio. Adding paper to compost without providing additional material to lower the C:N ratio can slow degradation and prolong composting times. Mixing nitrogen-rich material (fertilizer, food waste, sewage sludges, etc.) can bring the C:N ratio down to ideal conditions. When possible, natural sources of nitrogen (food waste and sewage sludge) should be chosen over chemical fertilizers because studies have shown that cellulose degrades faster when part of a diverse feedstock (NCASI 1993). This is presumably due to an increase in diversity of the microbial community, resulting in increased degradation of cellulose.

Increased size and thickness of paper products can negatively impact degradation in compost piles, although results can vary based on product. One study showed that doubling the layer (stacked sheets) of recycled paper reduced degradation by almost 20% when compared to a single layer sample of the same paper. However, in the same study, single- and double-layered samples of bleached hand towels degraded at identical rates (Venelampi et al. 2003). To avoid potential impacts, paper products should be reduced in size (shredded) to increase surface area and promote mixing before being added into compost piles (MOECC 2016).

Maintaining high oxygen concentrations through proper mixing, while still maintaining temperatures for prolonged thermophilic phases, is crucial for biodegradation of paper in a reasonable time period. Deviations in either can result in compost with undecomposed paper remaining, requiring extended periods of time to fully degrade the paper.

When properly maintained, composting using paper feedstock can result in a final product that is high in quality, sufficiently stable, free of odors, and can be marketed for agricultural uses (NCASI 1993). Properly composted paper has also been shown to have no impact on plant germination rates. In fact, results from one study showed final yields for plants grown in paper compost were higher than for plants grown in compost without paper or commercial growth substrates (Venelampi et al. 2003).

4.2 Bleached paper

Bleaching pulp removes residual lignin remaining after the pulping process, brightening the final product and further increasing the percentage of cellulose fibers. The removal of lignin complexes can increase exposure of the cellulose fibers, increasing microbial access. Bleaching also involves hydrolysis and oxidation reactions which can further increase biodegradability (Andrady et al. 1992).

In a laboratory study, Venelampi et al. (2003) measured the biodegradability of several paper products by comparing CO_2 evolved from the sample to the theoretical maximum CO_2 evolution of the sample (calculated based on organic carbon content). Even with a relatively short study time (45 days) all paper products made from chemical and bleached pulp generated more than 70% of the theoretical amount of CO_2. The sample of uncoated, bleached Kraft paper resulted in 92% biodegradability, the highest of all products tested.

4.3 Unbleached paper

Unbleached paper can have varying and at times relatively high lignin content (up to 20% by weight) depending on pulping process and desired final product. This residual lignin can impact results of composting experiments by reducing the overall biodegradability of the paper product. The laboratory experiment conducted by Venelampi et al. (2003) showed significantly lower biodegradability rates for unbleached paper (56 – 70%) compared to bleached products. The authors concluded that the poor biodegradability of unbleached samples was the result of high lignin content. Lignin itself is recalcitrant and resistant to biodegradation, but the presence of lignin in paper can also reduce the biodegradability of cellulose by covering the fibers and protecting them from microbial attack. Lignin inhibition of cellulose biodegradation has also been observed in anaerobic degradation of paper (Micales and Skog 1997).

High lignin content of paper can cause low biodegradability results in experiments, which may appear unfavorable especially when compared to bleached paper products; however, it is important to remember that while some lignin can be mineralized to CO_2 during composting, most lignin in paper is degraded into a stable humic substance (Tuomela et al. 2000). This humic material provides many of the benefits associated with compost and can be a desired end product.

4.4. Paper with surface coatings or additives

Surface coatings and additives are applied to paper products to produce or improve a desired quality in the final product. Dry strength additives are used to improve the physical properties of the dry paper sheet. Wet strength resins protect the fiber bonds from reacting with water allowing the paper to maintain strength even after wetting. Surface coatings are used to provide a barrier, protecting the underlying paper from water, air, or grease (Smook 2016). A wide variety of these additive and coating materials exist. The unique chemical properties of these materials can impact how they behave in a compost environment.

The laboratory experiment conducted by Venelampi et al. (2003) tested several paper products using wet strength additives. In general, the additives reduced the percent biodegradability in the experimental time frame. For example, a sheet of bleached high density paper with a wet strength of 30% only reported a percent biodegradability of 77%, lower than the 92% biodegradability of bleached kraft paper with no additives. Bleached paper with additives did report higher percentages than unbleached papers with no additives, suggesting lignin has more of an impact for this particular metric than certain additives. Later experiments using longer composting time periods (120 days) showed papers using wet strength additives can achieve near 100% biodegradability in that time frame.

In lab and field composting studies, Andrady et al. (1992) showed that in general, biodegradation was slower for coated/laminated papers, but did not limit the overall decomposition process for certain coatings. In laboratory experiments, the biodegradability of bleached, high density paper with silicone coating was 75%, but was eventually able to achieve 100% biodegradability with sufficiently long composting times (Venelampi et al. 2003). Paraffin wax coatings have been shown to be readily biodegradable. Waxed corrugated cardboard in one study was easily decomposed during composting (Raymond et al. 1997). In another field experiment, wax coated paper cups reported the highest decomposition rates in the field even when compared against uncoated plain card stock (Andrady et al. 1992). In the same experiment, paper products using polyethylene coatings were also tested. As with the other coatings, the PE reduced the rate of biodegradation, but given sufficient time the paper portion was eventually biodegraded. However, the study noted the plastic film lamination remained after extensive accelerated soil-burial exposure. These results indicate that certain paper coatings are not biodegradable during composting.

4.5 Full-scale examples

Results from five municipal solid waste composting facilities using paper feedstock were reported by NCASI (1993). Each composting operation was unique in terms of its composting technique, producing varying results. Facilities using short composting times of 7, 14-30, and 40 days produced compost with either a strong odor or with paper structure still intact in the compost particles. Odor issues could be remediated with additional curing time. One facility used aerated, static piles (not turned), which left paper structure intact in the final product. The single facility that composted for an appropriate length of time, turning piles periodically, produced compost with no visual evidence of paper and a mild, earthy odor. The author concluded that compost operations providing ideal conditions for moisture, aeration, temperature and time (12-15 weeks) could produce a high-quality compost from municipal solid waste and paper that was suitable for horticultural uses.

Venelampi et al. (2003) conducted two full-scale studies using 100% recycled hand towels. When fully incorporated into a compost pile, the paper samples degraded rapidly showing no visible signs of paper in the final product after 16 weeks. When mixed with biowaste and buried in nylon fabric bags, biodegradability results were highly variable with generally low biodegradability, even with extended composting times. The piles using nylon bags were not turned during the experiment and the authors concluded the reason for low degradation was likely due to sustained periods of low oxygen and high temperatures. The variable results showed that full-scale composting is highly dependent on process conditions (size, time, aeration, nutrients, etc.). The authors noted that moisture content was especially important in the early stages of degradation, especially when composting paper products.

5.0 Summary

Recommendations for including paper and paper products during composting are commonly contained in general guidance documents concerning this subject. These recommendations make sense given that paper is a natural product derived from wood, which should make it an ideal feedstock for composting (Venelampi et al. 2003). While information on composting paper in the scientific literature is relatively sparse, a handful of studies have focused on this specific topic.

Findings in the literature, for the most part, support the use of paper for composting. Results of paper composting will be highly dependent on process conditions, but if proper conditions are provided for a sufficiently long period of time, studies show that paper can be used to produce a high-quality, stable compost. It is particularly important to maintain appropriate levels of oxygen and moisture and balance inputs to ensure an optimal C:N ratio. Reducing paper particle size with shredding can increase surface area and accelerate biodegradation. Longer composting times will be required compared to more labile carbon feedstocks (e.g., food waste). Times will vary depending on the exact paper product, but 12 – 15 weeks has been suggested as an appropriate length of time.

The type of paper product used can also impact results. In general, bleached, uncoated papers have the highest rates of biodegradability. Unbleached paper may not be 100% biodegradable during composting due to the higher lignin content, but the modified lignin resulting from composting produces a stable humic-like substance valued in the final compost. Coatings and additives appear to reduce the rate of biodegradation during composting, but given enough time, most paper products with coatings and additives will be completely degraded. It has been shown that certain, non-biodegradable coatings such as polyethylene can persist into the final compost product. Where such coatings are present, the impacts on final compost quality may need to be considered.

Full-scale studies specifically investigating the use of paper for composting highlight the variability of results when ideal conditions are not provided. When unfavorable conditions are employed, the final compost product can have undesirable properties such as odor or residual paper particles. However, these studies also show that when compost piles are properly maintained, paper feedstock can produce a stable and valuable final product.

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