# Composting a combined RMP/CMP pulp and paper sludge

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**ABSTRACT** *Two 1100-L primary–secondary sludge (3:1 by volume) samples from an RMP/CMP newsprint mill were composted for six weeks using a static-pile, forced-aeration process in insulated reactors with different control regimes. The raw sludge was nonhazardous and was easily composted without a bulking agent or urea amendment. Composting rate was unaffected by moisture content over the range investigated. Little change in mass or volume was observed except for water loss. The six-week-old composts produced in the two reactors were similar, with physical and chemical properties suitable for plant growth. Germination of lettuce seeds was similar in extracts from both composts and from peat moss. The growth of tomato plants in soilless media amended with six-week-old composted sludge was comparable with growth in a peat-moss-amended medium. Two variables—cation-exchange capacity and total humus content—were strongly correlated with compost age and plant growth. This suggests that these two physical properties could be used as predictors of compost maturity in an industrial compost facility.*

KEYWORDS
Composting
Landfill
Land use
Sludge disposal
Solid wastes
Waste management

The U.S. pulp and paper industry generates approximately 100 lb of sludge per ton of pulp (*1*). With an annual pulp production of 80 million tons, this works out to 4 million dry tons of sludge per year. The vast majority of sludge is now being landfilled (70% in 1988) (*1*), but environmental concerns and governmental regulations have made landfills more expensive to operate and much harder to site. Consequently, alternative methods of sludge management are being evaluated.

Sludge incineration is the most widely practiced of the alternative disposal methods, with 21% of the sludge being disposed of in this manner (*1*). However, the high water and ash contents in sludge make it a poor fuel and cause furnace fouling problems. Land application of raw sludge has been practiced for years and appears to be a safe, economic alternative to landfilling (*2-5*). Approximately 8% of the generated sludge is currently being land applied (*1*). However, concerns about the toxic effects of the organic residues produced from chlorine-based bleaching processes may limit land application of kraft sludges. The EPA recently proposed a rule that would limit TCDD/TCDF (tetrachlorodibenzo-*p*-dioxin/tetrachlorodibenzofuran) soil concentrations to a maximum of 10 parts per trillion (*6*).

Composting is a third alternative that could find increased use in the future. Composting could be used to reduce sludge mass and thus hauling costs, reduce odor, degrade compounds that are toxic or inhibitory to plant growth, decrease C:N ratio and prevent nitrogen immobilization when applied to soils, potentially biodegrade chlorinated organics, and produce a higher-value material suitable for horticultural and agricultural applications.

Composting is the aerobic decomposition of organic matter into a stabilized material with a higher humic acid content. Such materials can be used as a soil amendment (*7, 8*). All types of organic wastes can be composted using technologies that range from simple windrows to highly controlled in-vessel composting systems. Industrial composting processes include static piles (windrows with periodic turning), aerated static piles (piles with air distribution pipes), and bioreactors (vessels with controlled aeration, moisture, and temperature). Composting time can vary from a few weeks to several years, depending on the intensity of the process and the compost quality desired. The rate of decomposition, stabilization, and humification depends on the organic substrates present. For example, highly lignified, cellulosic wastes will compost at a slower rate than food wastes and municipal sludge.

The rate and extent of composting are governed by several variables, some of which must be within specific optimum ranges to promote microbial activity, pile heating, and rapid stabilization of the organic materials. The important variables include moisture content (40–70%), C:N ratio (20:1 to 40:1), aeration rate (5–15% $O_2$ in pile), temperature (20–60°C), pH (5.5–8.0), and particle size or porosity sufficient to provide aerobic conditions in the pile (*8*).

The composting process has four distinct phases involving mixed populations of bacteria and fungi: initial mesophilic phase, thermophilic phase, second mesophilic phase, and curing phase. During the initial mesophilic and thermophilic phases, a large amount of heat is generated when bacteria rapidly metabolize simple, low-molecular-weight compounds. During the thermophilic phase, temperature must be maintained below 60°C to avoid thermal inhibition and death of the microbial population. Transitions from mesophilic to thermophilic and then to second mesophilic phases are distinguished by changes in bacterial population at approximately 40°C. As simple compounds are depleted by microbes, a second mesophilic phase ensues during which the compost cools. Fungi become more important during this phase, as they attack more-complex components such as cellulose and hemicellulose. The curing phase lasts from several months to years as the organic carbon is transformed to stable humic compounds.

Stabilized compost is typically neutral, with a C:N ratio of <30:1. The composting process oxidizes simple, carbon-containing substrates to carbon dioxide, thereby decreasing the carbon-to-nitrogen ratio in the compost. When used as a plant growth medium, compost will not contribute to mineralization of nitrogen in soils as commonly occurs in land application of fresh, uncomposted, lignocellulosic wastes. In addition, compost improves soil properties and plant growth by increasing soil aeration, improving water-holding capacity and water infiltration, and reducing bulk density and surface crusting. Compost has been used in horticultural and agronomic crop production, land reclamation, vegetation establishment, and erosion control (*8*).

## Previous studies of sludge composting

In the future, composting processes could be used in the pulp and paper industry to reduce sludge weight, moisture content, and C:N ratio. With a lower C:N ratio, the compost could potentially be applied to soil at much higher rates than raw sludge. Several pilot- and full-scale studies have demonstrated the feasibility and advantages of composting combined primary–secondary sludges from a kraft pulp mill (*9–17*). For example, Crown Zellerbach conducted pilot composting studies over 236 days on a combined primary–secondary kraft sludge. Wysong (*9, 10*) reported volume reductions of 34–52% and total weight losses of 32–46% (mainly water loss) and projected that composting could cut transportation costs by 50%.

Boise Cascade (*11*) is currently composting a 65%-organic/35%-ash primary sludge with a moisture content of 77–83%. Paunch from a slaughterhouse is added to increase the nitrogen content, and the amended sludge is then composted for several months prior to disposal in a landfill. The primary purpose of this composting process is to reduce mass and volume, which conserves landfill space. Potential leachate problems are also reduced (*12*).

P. H. Glatfelter Co. (*13, 14*) developed a commercial process in the late 1970s to compost a bleached kraft primary–secondary sludge containing 40% ash and 70–78% water. Sludge was first shredded, mixed with bark to improve porosity, and then placed on plastic aeration pipes. Aerated, static piles were composted for three weeks and then cured for several more weeks. Pile temperatures of 60–77°C destroyed any potential pathogens. After composting, the material was screened, and the bark was recycled as a bulking agent. The 65:35 blend of sludge compost and bark fines had a pH of 6.8–7.2 and could be used as a farm soil conditioner at 75 $m^3$/acre to loosen clay soils and as a substitute for peat moss in horticultural applications.

Einspahr *et al.* (*17*) conducted the only study to date on the effect of pulp and paper sludge compost on soil properties. This study compared a raw recycled-paper primary sludge, a raw chemimechanical primary sludge, and primary sludge from a kraft pulp mill (raw, composted, and vermicomposted or worm-worked). All five sludges significantly improved the available moisture and cation-exchange capacity of the soils and thus would reduce irrigation and fertilization requirements. The kraft sludges that were composted and vermicomposted provided the greatest improvement in soil properties.

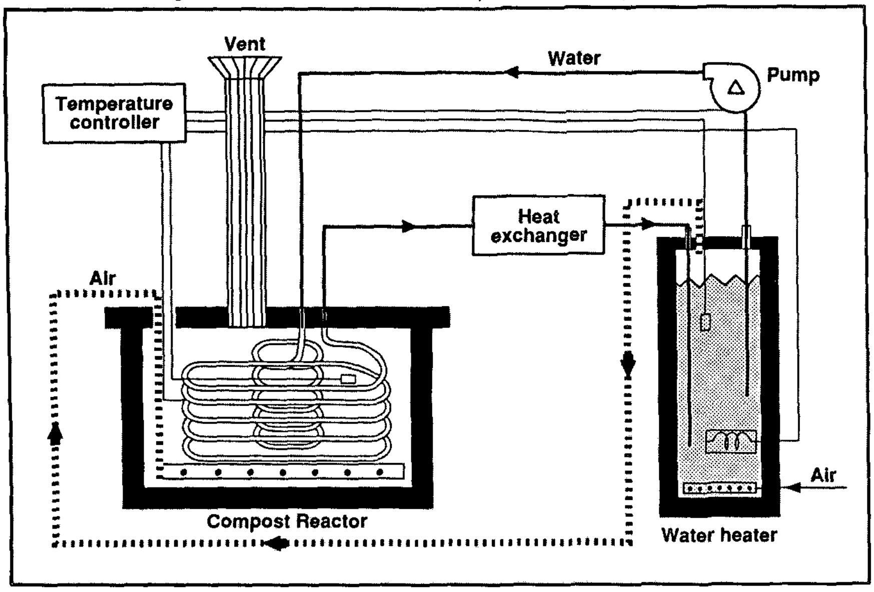
## Research needs and project objectives

Although research to date on composting pulp and paper sludge has been encouraging, many important practical and fundamental questions have yet to be addressed. Research is needed to evaluate (a) process variables that could be used to control the composting process and (b) physical and chemical changes in the compost that could be used to follow the course of composting.

Future research also should include plant growth bioassays to monitor the rate of disappearance of toxic or inhibitory compounds during composting and to demonstrate that the compost is suitable as a plant growth medium. Greenhouse and field trials should be conducted to gain regulatory approval and to demonstrate compost value and potential markets. Research is also needed to determine if composting could be used to biodegrade chlorinated organic compounds in primary, secondary, and lagoon sludge, as suggested in recent field research on chlorophenol-contaminated soils (*18*). The results of that research showed that after four months of composting, chlorophenol soil concentrations were reduced by 86%, from 212 mg/kg to 30 mg/kg.

Mechanical pulp and paper sludges should be particularly amenable to composting because they are nontoxic, and their coarse texture facilitates aeration. The objectives of this project were to develop a composting process

1. Reactor 2, designed to control moisture and temperature of composted material




for RMP/CMP (refiner mechanical pulp/chemimechanical pulp) sludge and to evaluate the compost as an amendment in a plant growth medium. Specific goals were to monitor physical, chemical, and inhibitory/phytotoxic changes in the sludge over a six-week composting period in order to evaluate the extent of composting and compost maturity. Germination of lettuce seeds and bioassays of tomato plant growth were used to compare plant growth responses as a function of composting time.

## Experimental procedures

### Sludge collection and preparation

Two 1100-L samples of fresh, screw-pressed sludge were collected from an RMP/CMP newsprint mill pulping mainly spruce, fir, and hemlock. Combined primary and secondary sludges (3:1 by volume) were shredded on a Royer soil shredder, loaded into two 1560-L pilot-scale bioreactors within 5 h of collection, and composted for six weeks using a forced-aeration, static-pile process. Sludge in Reactor 1 (Compost 1) was amended with urea from a C:N ratio of 33:1 to 20:1, whereas the sludge in Reactor 2 (Compost 2) was unamended. The combined sludges contained adequate moisture (55% and 60%) and porosity, and thus neither parameter was adjusted.

### Reactor design and control

The bioreactors consisted of tapered cylindrical fiberglass tanks with a height of 91 cm, a bottom diameter of 145 cm, a top diameter of 152 cm, a total volume of 1560 L, and a working volume of 1100 L. The tanks were covered with hinged wooden tops and insulated on all sides with R-19 fiberglass insulation. The reactors were aerated with compressed air distributed through 1.6-mm holes in 2.5-cm-diam. PVC pipes (header and lateral) on the bottom of the tanks. Reactor gases were vented through a 10-cm-diam. PVC pipe and scrubbed with a fine mist sprayer to reduce odor. Temperature in both reactors was measured and controlled with an Omega CH 320 temperature controller and a single J-K thermocouple located in the central upper third of each pile. Time-temperature profiles were recorded on a strip chart recorder.

Reactor 1 was designed to control temperature at 60°C or below. When temperatures were below 60°C, Reactor 1 was aerated with ambient air using a 3-min-on/15-min-off cycle. When temperatures rose above 60°C, the pile was cooled by continuous aeration. Air flow rate was adjusted manually to maintain a maximum temperature rise during the initial mesophilic phase. During the second mesophilic stage, air flow was manually adjusted to maintain approximately 10% oxygen in the pile, as measured with a Bacharach Fyrite II gas analyzer. Moisture content of the compost in Reactor 1 was allowed to decrease naturally as the internal heat and aeration dried the compost.

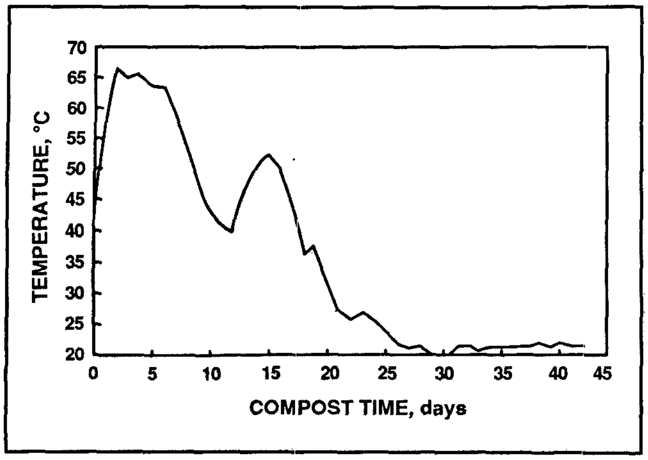
Reactor 2 was designed to independently control moisture content at 60%, oxygen content above 15%, and temperature at or below 60°C. Figure 1 is a schematic diagram of Reactor 2. The initial moisture content of 60% was maintained in the pile by using water-saturated air for aeration. Air was bubbled through a water reservoir maintained at 1°C below the compost temperature by a differential controller adapted from Sikora *et al.* (*19*) by Scheirman (*20*). When reactor temperatures exceeded 60°C, the compost was cooled by overriding the heater and circulating water through an external and an internal heat exchanger in the pile until the temperature dropped below 60°C. Reactor 2 also had the capability to fully control the time-temperature profile and simulate a desired composting regime, although this function was not used in this study.

### Compost sampling and analyses

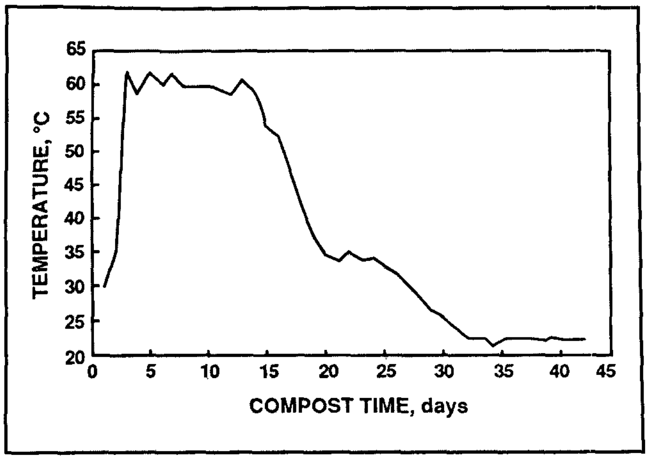
Twelve random samples of equal volume were collected weekly from four quadrants of the reactors at three depths and then mixed to yield a composite sample. The quadrants were rotated by 60° each week so that the pile was uniformly sampled. Physical analyses and tomato growth comparisons were conducted using fresh compost, whereas chemical analyses and seed germination tests were conducted using compost that had been frozen for one to six weeks. With the exception of the elemental analyses for sludge and tomato foliage, all chemical and physical analyses were measured every week in triplicate and then averaged.

Available P and K (*21*, *22*), electrical conductivity (*23*, *24*), C:N ratio (*25*), pH (*26*), cation-exchange capacity (*27*), extractable cations (*28*), and total cations as obtained by nitric/hydrochloric acid digestion (*29*) and analysis on an ICP (Leman Labs Model PS 3000) were measured by the Analytical Services Laboratory at the University of Idaho following standard procedures for soils. Extent of humification as measured by the fulvic acid, humic acid, and total humus content was measured using the method of Sugahara and Inoko (*30*). Total carbon and organic nitrogen in the compost-water extract (*31*)

**2.** Time-temperature profile for Reactor 1




**3.** Time-temperature profile for Reactor 2




was measured by BC Research in Vancouver, B.C.

Bulk density of the compost was measured in a 2.0-L container by first filling it to the top, dropping it four times from a height of 8 cm, and then refilling to the top and striking level as adapted from ASTM E 873-82. Moisture content was measured according to ASTM D 2016-74, and volatile solids and ash content were measured according to ASTM D 1102-56. Air- and water-holding capacity of the container media used for growing the tomato plants were measured in 15-cm-diam., 13-cm-high pots as described by Holstead (*32*).

#### Bioassays

Compost extracts were tested for their effect on lettuce seed (*Lactuca sativa*, "Bentley Simpson's Curled") germination using three replicates per extract (*33*). Twenty grams of oven-dry equivalent compost and peat moss were extracted with 250 mL of distilled water at 60°C for 1 h with shaking. The extract was decanted and then filtered through a Gelman fiberglass filter. Fifty seeds were placed on Whatman No. 2 filter paper in petri dishes with 5 mL of compost or peat moss extracts and 2 mL of 15m*M* $KH_2PO_4$ buffer (pH 6). Distilled water (5 mL) plus 2 mL of buffer was used as a control. Petri dishes were covered, sealed, and incubated in a growth chamber at 28°C under continuous light (225 $\mu$mole/m$^2$s). A germination index was obtained by counting the number of protruding radicles after 24 h, 48 h, and 72 h.

The effects of composted sludge on plant growth were compared using 14-day-old tomato seedlings (*Lycopersicon esculentum*, "Dombito"). Individual tomato seedlings were planted in 15-cm pots with five plants per treatment in a medium amended with sludge compost collected at weekly intervals. Potting media consisted of a 1:1:1 mixture by volume of silica sand (20/30), perlite, and compost or peat moss (control). The pH of the peat-moss-amended medium was adjusted with dolomite as in U.C. mix E (*34*) to pH 5.5. Tomato plants were grown in a growth chamber under a 16-h day (28°C and 285 $\mu$mole/m$^2$s) and an 8-h (23°C) night cycle. Each plant was fertilized weekly with 250 mL of Rapidgro® solution (mixed as recommended for tomatoes) and watered as needed (almost daily).

After 30 days, plant growth indices were measured to determine the effects of the potting medium on tomato seedlings. Leaves were removed from the shoots, and then the shoot was detached from the roots. Roots were washed free from the growth medium. Leaves, stems and roots were dried for 72 h at 70°C in a vacuum oven and then weighed to obtain total biomass. For foliar analyses, stems and leaves were combined, digested, and then analyzed on an ICP to determine elemental content (*35*).

## Results and discussion

#### Bioreactors and time-temperature relationships

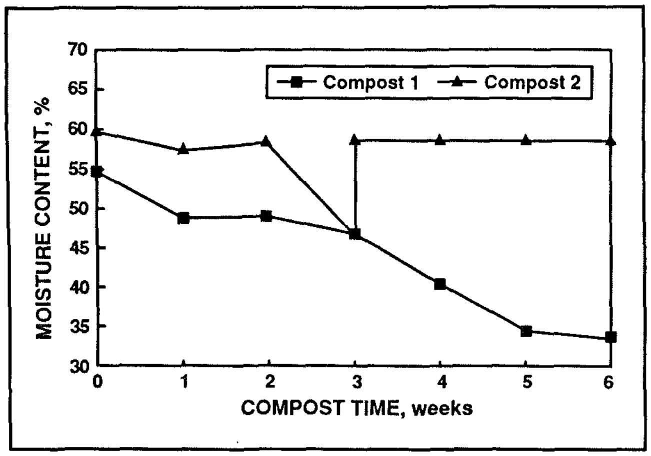
The pilot-scale reactors used in this project were unique in size and design. Reactor 1 controlled temperature at 60°C or below during the thermophilic phase using intermittent or constant aeration. Reactor 2, illustrated in Fig. 1, controlled moisture content (≅60%), oxygen content (>15%), and temperature (≤60°C).

The time-temperature relationships observed in the two reactors were similar, as seen in **Figs. 2 and 3**. Both reactors progressed through the typical mesophilic, thermophilic, and second mesophilic phases over a three-week period. Maximum temperatures were reached in approximately 72 h, dropping to 30-35°C after three weeks. During the thermophilic period, Reactor 2 was controlled effectively at a maximum temperature of 60°C (±2°C), while Reactor 1 ranged somewhat higher (60-67°C).

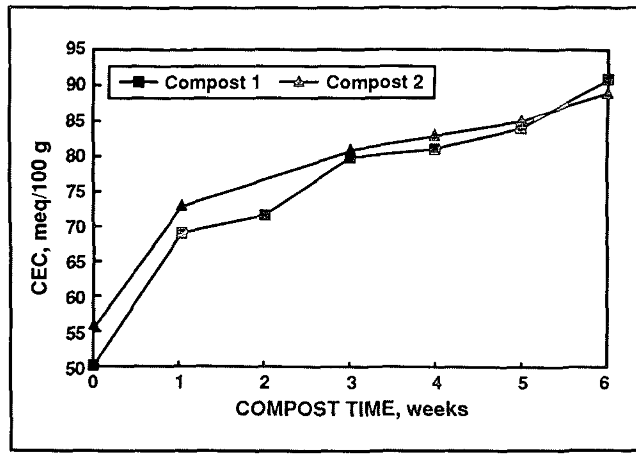
The rapid temperature decrease in Reactor 1 for days 7 through 12 was due to excessive aeration and subsequent cooling of the pile. When the air flow rate was reduced on day 11 to provide 10% rather than 15% $O_2$ in the pile, a second temperature rise was observed. This lack of control in Reactor 1 demonstrated the advantage of using continuous aeration with saturated air at compost temperature, as in Reactor 2. However, the gain in control required more hardware and produced wet regions in the pile near the surface of the heat exchanger.

**Figure 4** shows the moisture contents of the two reactors over the six-week compost period. Without humidity control, moisture content in Reactor 1 dropped from 55% to 34% over the course of the experiment as water was lost during aeration and pile heating. Reactor 2 maintained a constant moisture content of 60% except between weeks 2 and 3, when a thermistor failed on the differential

**4.** Compost moisture content as a function of compost time




**5.** Cation-exchange capacity as a function of compost time




controller. After the error was corrected, the compost moisture content was readjusted back to 60% with distilled water. Compost moisture content remained constant thereafter. Based on physical, chemical, and plant growth characteristics, the composts produced in Reactors 1 and 2 were very similar, which implied that moisture content, over the range investigated, had little, if any, effect on the rate of composting. In an industrial composting process, reducing the moisture content of the compost would reduce transportation costs and increase the heating value if the compost were to be incinerated or used as a fuel.

### Sludge and compost properties

Chemical characteristics of a typical primary, secondary, and combined RMP/CMP sludge from the newsprint mill are shown in **Table I.** The raw sludges had a near-neutral pH of 6.4 to 6.6 and, as seen in **Table II,** the concentration of heavy metals in the sludge was comparable with that of average soil and much lower than a municipal sewage sludge. **Table III** compares the physical and chemical properties of raw sludges (zero weeks), composted sludges (six weeks), and peat moss. The pH as well as the total and extractable elements in both composts were essentially unchanged throughout the composting period. Both composts contained higher nutrient concentrations, such as phosphorous and potassium, than peat moss. Based on the chemical composition, raw and composted sludges could be used safely and beneficially in agricultural, horticultural, and forestry applications.

Electrical conductivity of the raw sludges was 0.53 dS/m for Compost 1 and 0.98 dS/m for Compost 2. For comparison, the electrical conductivity of peat moss was 0.51 dS/m. The difference in electrical conductivity between the two composts had little, if any, effect on plant growth.

Only a small portion of the organic matter in the sludge was oxidized to $CO_2$. Total dry mass of the compost decreased by only 2% over the six weeks of composting, as shown in Table III by the slight increase in ash content and the slight reduction in volatile solids. A previous study with pulp and paper sludge (*9*) found mass losses of 32-46% (wet basis) and volume reductions of 34-52%. Our results indicated that most mass losses observed in composting this sludge were due to water loss rather than carbon loss. The results were reasonable, since wood and its components (cellulose, hemicellulose, and lignin) would be relatively resistant to rapid decomposition over a six-week period.

Odors were produced during the composting process, as is common with most sludges. After the second week, however, the sludge had an earthy odor. Bulk densities as well as air- and water-holding capacities of the container media remained essentially constant over the six-week period. Both composts had an average bulk density of 0.27 g/cm$^3$ (dry basis). Container media amended with Composts 1 and 2 had an average air-holding capacity of 20-21% and a water-holding capacity of 10-11%. For comparison, the peat-moss medium had air- and water-holding capacities of 17% and 13%, respectively.

The rate or extent of composting in Reactor 1 was unaffected by amending the sludge from a C:N ratio of 33:1 to 20:1 prior to composting. After six weeks of composting, the C:N ratio increased from 20:1 to 30:1, suggesting that most of the nitrogen in the urea was lost through ammonia volatilization. The C:N ratio in Compost 2 was essentially unchanged over the six-week composting period, which is consistent with the small reduction in volatile solids (2%). Neither the C:N ratio nor C-total:N-organic ratios in the water extracts showed meaningful trends that could be used to predict the extent of composting.

Cation-exchange capacity and total humus content for both composts increased with compost age, as seen in **Figs. 5 and 6.** The increase in cation-exchange capacity was probably due to oxidation of organic components to carboxylic acids that are capable of exchanging cations. The cation-exchange capacities of both composts increased from 50 meq/100 g and 55 meq/100 g to approximately 90 meq/100 g after six weeks of composting as compared with 144 meq/100 g for peat moss. The increase in cation-exchange capacity would improve retention and availability of plant nutrients. Although total humus content in the sludges increased with composting time, the PQ index did not change significantly. The PQ index estimates the change in the molecular-weight distribution of the humic materials (ratio of humic acid to humic acid + fulvic acid). These results differed from an earlier study (*30*), which found the index to be correlated with composting time for municipal sludge and thus an indicator of compost maturity.

**Plant bioassays**

Seed germination and plant growth experiments were conducted as a function of composting time in order to evaluate compost stability and potential inhibition of plant growth. Germination of lettuce seeds was equivalent in compost and peat-moss extracts. All extracts, including peat moss, inhibited seed germination as compared with the water control. The inhibitory effect was unaffected by the time of composting, as seen in **Fig. 7**. After incubation for 72 h, seed germination in extracts of compost and peat moss approached 80–100% of that in water. The germination rate in peat-moss extract was 83% at 72 h.

Total biomass (leaves, shoots, and roots) of tomato plants increased with compost age, as seen in **Fig. 8**. This response is also typical of other composts in which inhibition of plant growth decreases with compost time (*37*). Tomato plants grew very little when planted in media that contained raw sludge or sludge composted less than two weeks. However, in weeks 2 through 6, dry biomass increased linearly; and after six weeks of composting, plant growth in compost was 90% of the peat-moss control. The improvement in plant growth with time of composting could have been due to the leaching, degradation, or volatilization of inhibitory or phytotoxic components, the increase in cation-exchange capacity, and/or the decrease in easily metabolized organic compounds, which cause rapid microbial growth and immobilization of nitrogen.

Leaves and petioles of tomato plants grown in five-week compost contained higher concentrations of N, Na, K, Zn, Mn, and Fe than those grown in peat moss, as seen in **Table IV**. Nutrient stress of tomato seedlings was observed for plants in peat-moss-amended medium as early as the fourth week of growth, but none was observed in the compost plants, probably because of the higher nutrient content of the original sludge. This reasoning was confirmed by a qualitative test using peat-moss-amended medium fertilized at twice the original rate and eight-week-old Compost 2 media fertilized at the original rate.

**I.** Chemical composition of a primary, secondary, and combined RMP/CMP raw mill sludge

| *Component* | *Primary* | *Secondary* | *Combined (3:1)* |
|---|---|---|---|
| pH | 6.36 | 6.63 | 6.43* |
| Ash, % | 4.2 | 9.9 | 5.6* |
| Electrical conductivity, dS/m | 0.19 | 3.90 | 1.12* |
| Nitrate-N, μg/g | <0.4 | 1.4 | 0.7* |
| Ammonium-N, μg/g | 12.4 | 948 | 132 |
| Sulfate-S, μg/g | 155 | 265 | 183* |
| Mineralizable-N, μg/g | 329 | 11,600 | 779 |
| Total elements, μg/g | | | |
| Phosphorus | 580 | 7,700 | 2,360* |
| Potassium | 120 | 2,000 | 590* |
| Calcium | 2,100 | 6,300 | 3,150* |
| Magnesium | 610 | 2,300 | 1,030* |
| Sodium | 440 | 1,300 | 655* |
| Sulfur | 1,500 | 7,000 | 2,880* |

*Data obtained by calculating a composite average based on a 3:1 primary:secondary sludge ratio rather than being measured directly.

**II.** Chemical composition of uncomposted RMP/CMP sludge, a typical soil, and municipal sludge

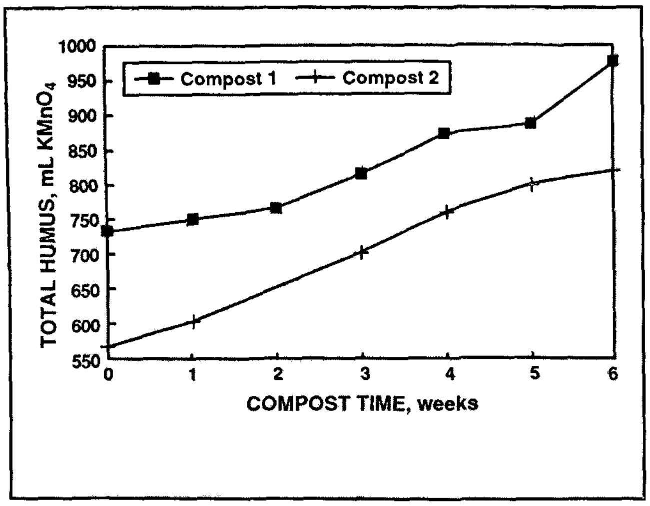
| | *Typical sludge* | | | | |
|---|---|---|---|---|---|
| *Element* | *Primary* | *Secondary* | *Combined (3:1)*[a] | *Average soil*[b] | *Municipal sludge*[b] |
| Lead, μg/g | 60 | 110 | 72 | 10 | 500 |
| Nickel, μg/g | 5 | 10 | 6 | 40 | 80 |
| Copper, μg/g | 7 | 45 | 17 | 20 | 800 |
| Cadmium, μg/g | <0.5 | <0.8 | <0.6 | 0.06 | 15 |
| Zinc, μg/g | 30 | 126 | 54 | 50 | 1700 |
| Chromium, μg/g | <12 | 30 | 17 | 100 | 500 |

[a]Data obtained by calculating a composite average based on a 3:1 primary:secondary sludge ratio
[b]Data obtained from literature (36)

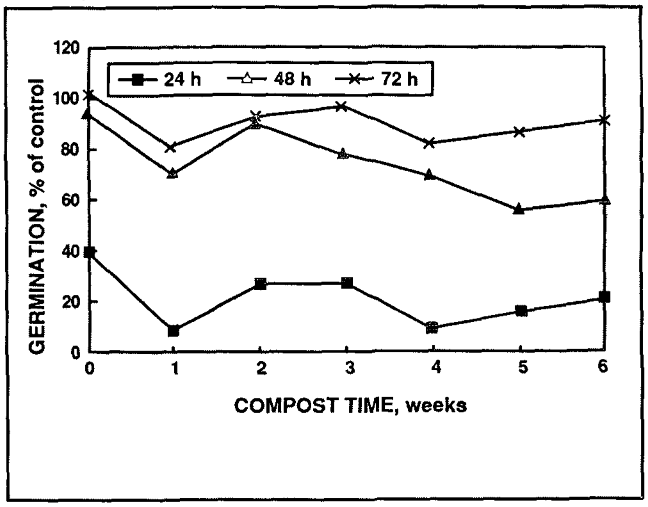
**III.** Chemical and physical properties of the raw sludges, six-week-old composts, and peat moss

| | *Compost 1* | | *Compost 2* | | |
|---|---|---|---|---|---|
| *Property* | *0 Weeks* | *6 Weeks* | *0 Weeks* | *6 Weeks* | *Peat moss* |
| pH | 6.5 | 6.7 | 6.6 | 6.9 | 4.5 |
| Moisture content, % | 55 | 33 | 60 | 60 | ... |
| CEC, meq/100 g | 50 | 91 | 56 | 89 | 142 |
| C:N ratio | 20 | 30 | 29 | 28 | 35 |
| Bulk density, g/cm³ | 0.268 | 0.249 | 0.261 | 0.272 | 0.117 |
| Volatile solids, % | 95.1 | 93.5 | 94.1 | 92.1 | ... |
| Ash content, % | 4.9 | 6.5 | 5.9 | 7.9 | 5.7 |
| Air capacity of container media, % | 22 | 19 | 18 | 20 | 17 |
| Water capacity of container media, % | 13 | 12 | 10 | 12 | 13 |
| Extractable elements, meq/100 g | | | | | |
| Potassium | 1.2 | 1.3 | 1.5 | 1.6 | 0.01 |
| Magnesium | 360 | 310 | 390 | 360 | 0.1 |
| Sodium | 170 | 170 | 150 | 170 | 0.01 |
| Calcium | 710 | 450 | 780 | 650 | 0.3 |
| Total elements, μg/g | | | | | |
| Potassium | 480 | 448 | 544 | 576 | 64 |
| Phosphorous | 267 | 386 | 238 | 265 | 27 |

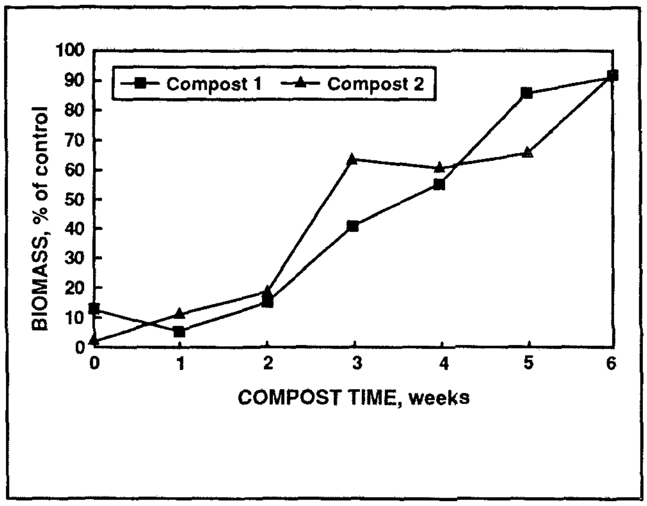
**6.** Humus content as a function of compost time



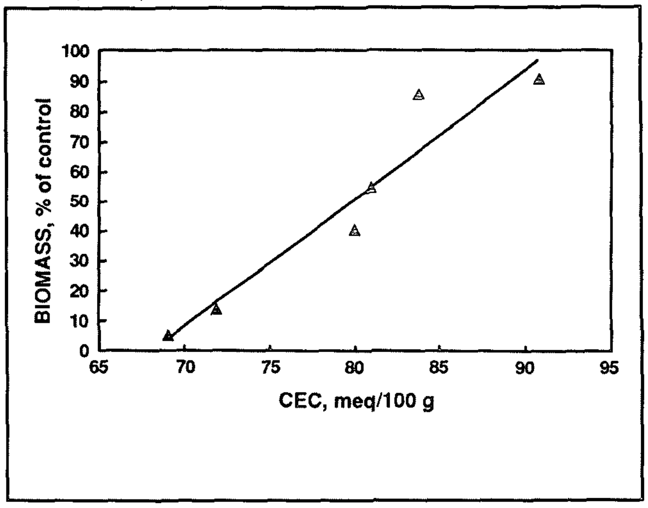

**7.** Germination of lettuce seeds in Compost 1 extract as a function of compost age and seed incubation time. (Germination in water control = 100%.)



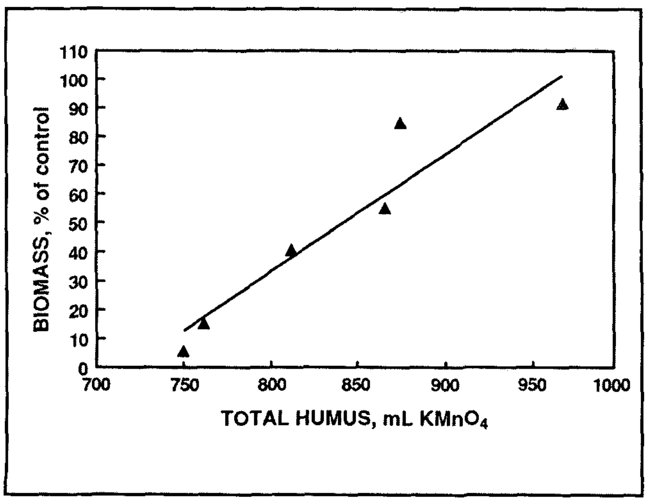

**8.** Change in tomato plant biomass as a function of compost time. (Growth in peat-moss control = 100%.)



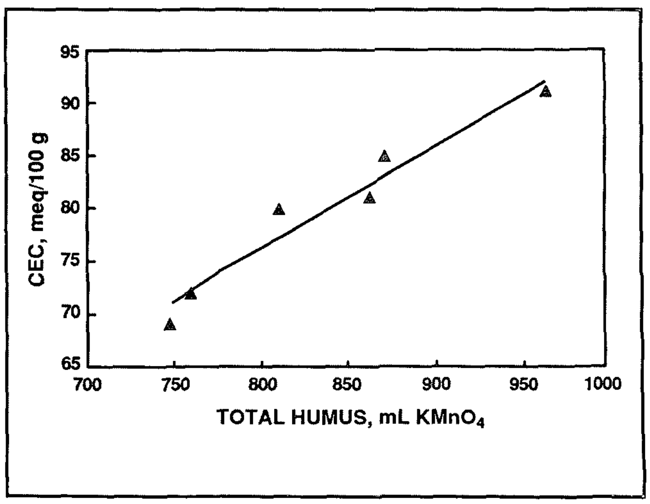

**9.** Relationship between cation-exchange capacity and plant biomass for Compost 1 ($r^2$ = 0.92)




**10.** Relationship between total humus content and plant biomass for Compost 1 ($r^2$ = 0.89)




**11.** Relationship between cation-exchange capacity and total humus content for Compost 1 ($r^2$ = 0.94)



Under these conditions, seedlings in the peat-moss medium lacked visible nutrient stress, but the sizes of plants grown in peat-moss- and sludge-amended media were similar to those in the six-week tests. These results indicated that the sludge and composts contained more plant nutrients than peat moss and therefore needed less fertilization.

### Correlations

Neither the C:N, C-total:N-organic ratio, nor PQ index could be correlated with compost age or with plant growth. In contrast, cation-exchange capacity and total humus content for both composts could be linearly correlated with plant biomass (weeks 1 through 6), as illustrated for Compost 1 in **Figs. 9 and 10**. Cation-exchange capacity correlations with composting time were $r^2$ = 0.92 and 0.94 for Composts 1 and 2, respectively. Humus content correlations with compost time were $r^2$ = 0.89 for both composts. Cation-exchange capacity and total humus content could also be linearly correlated with each other, as seen in **Fig. 11**, which depicts data for Compost 1. ($r^2$ = 0.94 for Compost 1 and 0.97 for Compost 2.) Recent work by Inbar *et al.* (*37*) also suggested that cation-exchange capacity and humus content could be used as potential indicators to predict the extent of composting. These results suggested that cation-exchange capacity and/or total humus could be measured periodically at industrial compost facilities to predict maturity and plant growth responses.

**IV.** Elemental composition of leaves and petioles of tomato plants grown in media amended with peat moss or five-week-old composts

| *Elements* | *Peat moss* | *Compost 1* | *Compost 2* |
|---|---|---|---|
| Calcium, µg/g | 10,596 | 8,702 | 8,566 |
| Potassium, µg/g | 15,788 | 17,321 | 17,044 |
| Magnesium, µg/g | 5,423 | 5,988 | 5,574 |
| Phosphorous, µg/g | 7,780 | 8,798 | 6,526 |
| Manganese, µg/g | 49.1 | 167.9 | 127.3 |
| Copper, µg/g | 10.64 | 9.45 | 6.92 |
| Zinc, µg/g | 60.78 | 79.09 | 74.74 |
| Iron, µg/g | 57.10 | 79.96 | 118.13 |
| Sulfur, µg/g | 1,217 | 1,256 | 1,618 |
| Sodium, µg/g | 1,094 | 1,775 | 1,973 |
| Nitrogen, % | 4.73 | 5.88 | 5.56 |

Data obtained using composite samples comprising five plants

## Conclusion

Two 1100-L primary-secondary sludge (3:1 by volume) samples from an RMP/CMP newsprint mill were composted using a static-pile, forced-aeration process in insulated reactors. One reactor controlled temperature at ≤60°C and moisture content at 60%, whereas the other reactor controlled only temperature at ≤60°C. Raw sludge was nonhazardous and could be easily composted without a bulking agent or urea amendment. Composting rate was unaffected by moisture content over the range investigated. Little change in mass or volume was observed except for water loss. After six weeks, the two composts were very similar, with pHs of 6.7 and 6.9, C:N ratios of 28 and 30, ash contents of 5% and 8%, and physical and chemical properties suitable for plant growth.

Growth of tomato plants in soilless media amended with composted sludge improved with time, and growth in the six-week-old composted sludge was comparable with growth in a peat-moss-amended medium. Germination of lettuce seeds was similar in extracts from compost and from peat moss. These pilot-scale results demonstrate that sludge from a mechanical pulp and paper mill can be rapidly composted into a material that probably can be used safely and beneficially in agricultural, horticultural, and forestry applications.

Cation-exchange capacity and total humus content were strongly correlated with composting time and plant biomass. Thus it may be possible to use these two physical properties to determine compost maturity in an industrial composting facility.□

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