Release of Trace Organics During MSW Decomposition and Environmental Implications of Waste Management Using Landfills and Waste to Energy

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North Carolina State University
Introduction

- Limited understanding of factors affecting NMOC production
- Increasing interest among state regulators
  - potential for over estimates based on US EPA defaults
    - NMOC increases as Lo increases
G is annual methane generation for a specific year $t$ ($\text{ft}^3\ \text{CH}_4/\text{yr}$);

$W$ is the annual burial rate (tons);

$L_o$ is landfill gas yield potential ($\text{ft}^3\ \text{CH}_4/\text{ton of waste}$);

$t$ is time after initial waste placement (yr);

$k$ is first order decay rate constant (1/yr)
Research Objectives

- Measure an ultimate NMOC yield for individual components
- Study the relationship between gas production and NMOC release
- Compare anaerobic and aerobic conditions
- Identify specific trace organic compounds
### Experimental Design

<table>
<thead>
<tr>
<th>Operation</th>
<th>Waste Type</th>
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<tbody>
<tr>
<td>Aerobic operation for 44/68 days prior to the onset of anaerobic conditions</td>
<td>Yard waste (I)</td>
</tr>
<tr>
<td>Traditional anaerobic operation (I &amp; II)</td>
<td>Yard waste (II)</td>
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<tr>
<td>Anaerobic decomposition of mixed paper (I)</td>
<td>Abiotic conditions (II)</td>
</tr>
<tr>
<td>Anaerobic decomposition of residential food waste (I &amp; II)</td>
<td>Control for background NMOC production from the leachate seed</td>
</tr>
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</table>
Reactor Setup
Reactor Operation

- Triplicate 8-L reactors
- Seeded with leachate to initiate decomposition
- Operated with leachate recycle and neutralization at 37°C
NMOC Yields for Individual Components

- **Abiotic MSW**: NSPS – 5.48
- **Anaerobic Yard Waste**: Phase I: 3.5, Phase II: 3.0
- **Aerobic Yard Waste**: Phase I: 0.5, Phase II: 0.4
- **Anaerobic Food Waste**: Phase I: 0.1, Phase II: 0.05
- **Aerobic MSW**: Phase I: 0.2, Phase II: 0.1
- **Anaerobic Paper**: Phase I: 0.0, Phase II: 0.0
Percent Yields for Methane and NMOCs at Midway Point of Operation
Speciated Organic Compounds

- Alkane
- Alkene
- Alcohol
- Chlorinated organic
- Ketone
- Aromatic
- Terpene
- Volatile Fatty Acid
Sources of Organics

- Household Hazardous Waste
  - chlorinated compounds, aromatics, alkanes, alkenes

- Vegetative Matter
  - terpenes release after plant death
    - present in citrus peels

- Decomposition Intermediates
  - alcohols, ketones and fatty acids

- Food Packaging
Alcohols
Butyric Acid
Propionic Acid

Biological Polymers
Cellulose
Hemicellulose

Soluble Monomers
Sugars
Amino Acids

Fermentative
Alcohols
Butyric Acid
Propionic Acid

Hydrolytics

Anaerobic
Biodegradation

H₂O
heat

CO₂
H₂O
O₂

Acetic Acid

CH₄

Methanogens

H₂,CO₂

CH₄

CO₂
Organics Released from Waste Components

43.1 62.8 179 363 1073 41.7 691 243 27.9 7.74 mg/dry gm

% of Individually Quantified Organics

Other
Chlorinated Compounds
Terpenes
Ketones
Alcohols
Aromatics
Alkenes
Alkanes

I         II         I          II  MSW-an       MSW-ae I         II         P
MSW-ab an
YW
FW

I
II
I
II
I
II
I
II
P
Comments on Specific Compounds

- Terpenes and ketones were dominant for most treatments
  - 10-20 compounds could account for 80 – 99% of yield
- Elevated Phase 1 food waste attributed to high citrus content
  - Pectin analysis, observation
- Toluene in yard waste traced to soccer field paint
- Styrene and toluene reported in high fat foods (cheese, butter, doughnuts)
Importance of Fatty Acids

- Acids analyses were conducted on worst case samples
  - High COD, low pH
- Acids accounted for 0.8% and 3.3% of NMOC yield for MSW-Ae treatments; and 3.3% for YW-ae
- Acids were not a significant contributor to NMOCs in any treatment
Comparison of AP-42 and Measured HAP Yields for MSW
Conclusions

- Lab-scale NMOC and VOC yields are considerably lower than regulatory estimates
- NMOC production is characterized by an initial “burst”, followed by much more gradual release
  - early gas collection is required to reduce NMOC emissions
Conclusions

- Food waste can be high in NMOCs, but is not a source of HAPs
  - Seasonal variability is important

- Decomposition intermediates (fatty acids) were not a major contributor to NMOC yields
Conclusions

- Aerobic treatment processes release significant NMOCs compared to anaerobic decomposition
  - Air sparging is a significant release mechanism based on the abiotic treatment
  - The elevated yields in the abiotic treatment suggests that significant biodegradation occurred in aerobic and anaerobic treatments
The Application of Life-Cycle Analysis to Integrated Solid Waste Management Planning for the State of Delaware

Use a planning tool to evaluate multiple alternatives for solid waste management in Delaware

- Consider cost, emissions, energy consumption
- Consider scenarios that may differ from current practice
Solid Waste Management is Complex: Many Options are Interrelated

- Recycling vs. waste-to-energy for recyclable paper and plastics (newsprint, cardboard, plastic)
- Relative benefits of landfilling or composting yard waste if we plan to recover methane?
- How do the cost and environmental emissions change if we add a material to a recycling program?
Solid Waste Management
Life-Cycle Inventory Model

- A computer model to assist in decision making
  - Quantitative information to screen waste management alternatives, optimize
    - cost, energy consumption, emissions
  - Compare many alternatives
    - Identify an optimal solution
    - Model existing waste management system
  - Perform sensitivity analysis on uncertain model inputs
- The person making a decision will still have to consider “unmodeled” factors
Modeling Solid Waste Management System in Delaware

- **New Castle County**
  - Urban
  - 64% of the state population

- **Kent County**
  - Suburban to rural
  - 16% of the state population

- **Sussex County**
  - Suburban to rural
  - 20% of the state population
Modeling Approach

- Each county was modeled separately
  - Represent individual facilities by county
  - Unique travel distances
  - More realistic

- Challenges
  - Appropriate combination of county-specific strategies to obtain appropriate statewide strategies
## SWM Strategies

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<th>Least-Cost</th>
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<th>Least-GHE</th>
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<td>Current</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
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<td>✔</td>
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<td>✔</td>
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</table>
Waste Flow Breakdown by Unit Operations
[current practice (base case)]

- Residuals Collection
- Pre-sorted Recycling
- Transfer
- MRF
- Landfill
- Diversion

% of Total Waste: New Castle, Kent, Sussex
Indicator Parameters for Environmental Emissions

- Particulate Matter
- Nitrogen Oxides
- Sulfur Oxides

Greenhouse Gas Equivalents, Thousands Tons/yr vs. Emissions, Millions lbs/yr graph
Variation of Mass Flows & GHE with Diversion

Least Cost: *curbside recycling* + *yard waste composting* + *combustion in New Castle County*

- Combustion is utilized to meet diversion constraint because it is estimated to be less expensive than alternatives
- Note partial implementation of combustion & utilization of a mixed waste MRF
- GHE increases near maximum due to composting
Variation of Cost & GHE with Diversion
[curbside recycling + yard waste composting + combustion in New Castle County]

- Cost and GHE increase near maximum case illustrate extremes of numerical solution
- Ash content of yard waste leads to use of composting
# Comparison of Cost and Emissions

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<tr>
<th>Parameter</th>
<th>Units</th>
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<th>Recycling</th>
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<th>Recycling + Comp MAX</th>
<th>Recycling + Combustion MAX</th>
<th>Recycling + Composting + Combustion MAX</th>
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<th>Combustion</th>
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<td>1.62E+08</td>
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<td>1.92E+08</td>
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<tr>
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<td>-8.84E+05</td>
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<td>-2.68E+06</td>
<td>-2.27E+06</td>
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<tr>
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Variation of Waste Flows, Cost, & GHE with Diversion
[curbside recycling + yard waste composting + combustion]

In Sussex County, a mixed waste MRF is utilized upstream of combustion to reduce transport costs.

Composting and curbside recycling only used near maximum diversion with resultant increases in GHE emissions.
Variation of Waste Flows & GHE with Cost While Minimizing GHE

[curbside recycling + yard waste composting + combustion]

- Increasing Cost constraint
- Combustion most effective but a mixed waste MRF utilized upstream in Sussex County to reduce transport of waste to N. Delaware
- GHE levels off prior to min GHE scenario
## Comparison of Cost and Emissions

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Observations from County-Wide Summary

- The least-cost and least GHE solutions vary by county
  - Use of a mixed waste MRF upstream of combustion
  - GHE from curbside recyclables collection in Sussex County
- Non-uniform utilization of curbside collection, combustion subject to a cost constraint
- Model led to counter-intuitive results
  - MRF upstream of combustion
  - Effectiveness of yard waste composting influenced by transport distance
- Model can be rerun with alternate assumptions
Procedure to Identify Statewide SWM Strategies

- SWM strategies are generated for each county
- Combinations of these strategies are explored to identify
  - Cost-effective diversion strategies
  - GHE-minimizing strategies at different costs
Identify the Cost-effective 30% Statewide Diversion Strategy?

<table>
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<tr>
<th>DIVERSION</th>
<th>Cost [$/yr]</th>
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<tr>
<td>30%</td>
<td>30%</td>
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<tr>
<td>30%</td>
<td>35%</td>
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<td>20%</td>
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<tr>
<td>40%</td>
<td>20%</td>
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Least-Cost 30% Statewide Diversion

Uniform diversion is not least cost case

For each county approximately 17 SWM strategies exist (20 – 88% diversion): 17 x 17 x 17 = 4,913 combinations should be analyzed for minimum cost…
Waste Flows in Cost-effective 30% Statewide Diversion Strategy
[curbside recycling + yard waste composting + combustion]

- Minimize cost subject to a diversion constraint
- Analysis similar to county specific analyses
- Combustion used subject to cost constraint
- Mixed waste MRF used in rural counties
County-Specific Contribution to Statewide Diversion
[curbside recycling + yard waste composting + combustion]

- The statewide optimum diversion strategy varies by county
- Between 50 and 70% diversion, all increases occur in New Castle County due to lower transport cost
GHE Breakdown in Cost-effective 30% Statewide Diversion Strategy
[curbside recycling + yard waste composting + combustion]
Variation of Waste Flows in Cost-effective Statewide Diversion Strategy
[curbside recycling + yard waste composting + combustion]

- Composting and curbside recycling only utilized near maximum diversion when combustion is enabled
Variation of Cost & GHE with Diversion in Cost-effective Statewide Diversion Strategy

curbside recycling + yard waste composting + combustion

- GHE increases at the extreme due to implementation of composting and curbside recycling to meet diversion constraint
Observations from Statewide Analyses

- The optimal statewide strategy is a combination of three unique SWM alternatives that are county-specific
  - a uniform statewide strategy will be sub-optimal
Generating Alternative SWM Strategies

- Optimal solution may not be appropriate
  - political feasibility
  - capital intensive
  - facility siting
  - …

- Generate alternatives that maximize differences in unit operations & waste flow choices in SWM strategies
Generating Alternative Strategies

Cost-effective 30% statewide diversion strategy includes:

- Cost-effective 35% diversion from New Castle
  Cost: $43.2 M/yr → $48 M/yr

- Cost-effective 20% diversion from Kent
  Cost: $20.2 M/yr → $22.5 M/yr

- Cost-effective 20% diversion from Sussex
  Cost: $34.6 M/yr → $38.7 M/yr
### Waste Flows for Alternative SWM Strategies to Achieve 30% Statewide Diversion

<table>
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<tr>
<th>Category</th>
<th>Units</th>
<th>Least-Cost</th>
<th>NC-Alt 1 + K-Alt 2 + S-LC</th>
<th>NC-Alt 2 + K-Alt 2 + S-Alt2</th>
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<td>%</td>
<td>30</td>
<td>30</td>
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</tr>
</tbody>
</table>

Three of 27 cases considered at each diversion level based on generation of 2 alternatives per county ($3^3$)
Consideration of Cost and Environmental Emissions Under Conditions of Uncertainty

- Objectives
  - Integrate uncertainty propagation procedures
  - Characterize and compare uncertainty in cost and LCI emissions estimates
Illustrative Results

- The procedure was applied to the cost-effective 30% statewide diversion case
- The least-cost and two alternatives were analyzed
Uncertainty in Cost of Strategies for 30% Statewide Diversion
[curbside recycling + yard waste composting + combustion]
Summary

- Developed new procedures to use the model for a complex statewide analysis
- Demonstrated modeling to generate alternatives and uncertainty analysis
- Quantified tradeoffs among cost, diversion, emissions
- Provided counter-intuitive and creative results
The Answer Is …..

- Humans must still make decisions
  - Consider combustion, mixed waste MRF
  - Can we vary solid waste management by county, or even neighborhood?
    - Use model to document cost implications of this decision
  - What are the appropriate cost and emissions targets?
  - Detailed engineering analysis
Reference


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