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ESM 219

2019/12/06

MITIGATING LANDFILL GENERATED GREENHOUSE GASES THROUGH METHANE OXIDATION

The United States generates an average of 250 million tons of organic municipal waste (MSW) per year that is distributed to the nearest proximate landfill of the country's 3000 active landfills (EPA, 2018). Ensuing bovine manure and rice paddy agricultural practices, landfills are the third-largest generators of arguably the most significant greenhouse gas (GHG) affecting climate change; methane (CH_4) (Abushammala, 2014). The production of methane in landfills is exacerbated by pivotal shifts in key variables such as an increase in temperature, pH levels of the soil, and precipitation that contribute to perturbations in the biogeochemical phases (Malgorzata, 2006). Under optimal conditions, the process of methane oxidation can be concurrent with methanogenesis, resulting in methane emission mitigation. Due to the sensitivity of the methane oxidation process, researchers and leading experts are developing new technology to exploit the capabilities of methane oxidation to reduce methane emissions from landfills.

Organic materials account for 40% of MSW in landfills, where it undergoes a complex biogeochemical decomposition process that triggers fluctuations in solid, liquid (leachate) and gas phases. During the decomposition of organic MSW, 90% of carbon is released in the gaseous form of CH_4, CO_2, and various hydrocarbons. These landfill gas emissions create complex public health complications regarding the release of bioaerosols and carcinogenic compounds, as well as substantial environmental implications regarding global warming and climate change (Pawlowska, 2006). While LFGs also contribute to photochemical smog in the atmosphere, landfill methane emissions, in particular, account for the most significant direct environmental impact on global warming and climate change than all other LFGs. A study by Henckel et al. (2001) found a linear rate increase of global CH_4 concentration over the past

200 years. Although this increased rate of CH_4 concentration in comparison with CO_2 levels is still relatively low, it is significant when compared to the global warming potential (GWP) index where CH_4 has 25 times the rate of GWP than CO_2. Landfill CH_4 emissions, in particular, account for 12% of the total global CH_4 concentration emissions.

To better understand CH_4 production, it is inherently valuable to understand decomposition phases of organic matter taking place in landfills. These phases consist of the initial phase, the transitional phase, acid production phase, methanogenic phase, and maturation phase. These phases are dependent upon time, and environmental variables such as - precipitation, soil pH, and temperature and could take years if not decades to reach completion. The initial phase consists of aerobic biodegradation of the introduced organic material on oxygen-rich surface levels. The transition phase begins with the hydrolysis and biodegradation of macromolecular substances through oxygen heterotrophs. Upon the depletion of oxygen, anaerobic conditions pave the way for acid fermentation and the production of methane. The final phase of methane oxidation occurs when there are no longer organic compounds to biodegrade (Pawlowska, 2006).

The CH_4 oxidation process is performed by aerobic, methanogenic bacteria that oxidize CH_4 to produce CO_2, H_2O, and microbial biomass ($CH_4+2O_2 \rightarrow CO_2+2H_2O$ microbial biomass) (Abushammala, 2014). Methanotrophs are categorized into three distinct classifications dependent upon the enzymatic pathways used for oxidation. Although unique in physiological characteristics, methanotrophs all retain the CH_4 monooxygenase (MMO) enzyme. MMO enzymes allow methanotrophs to oxidize CH_4 for energy yield. Furthermore, there are low-affinity and high-affinity methanotrophs which exhibit varying levels of oxidation capacities. Low-affinity methanotrophs, exhibiting high oxidation capacities, are prevalent in landfills.

Aforementioned, the process of methane oxidation is highly sensitive to inter-dependent environmental factors such as soil texture, organic content, moisture content, temperature, pH, and the availability of O_2 and CH_4 concentrations. Soil texture controls CH_4 emissions and oxidation rates dependent upon the porosity of the soil texture. For example, course soils have higher porosity and therefore have increased rates of oxidation. Furthermore, the presence of soil moisture and organic content symbiotically work together to increase oxidation rates. However, if soils become too saturated, it will limit the porosity that the texture of the soil allows. A study conducted by Whalen et al. (1990) of CH_4 oxidation on a closed landfill in Berkeley, found the decrease in soil moisture (11% to 5% H_2O) played a direct role in the decreased rate of oxidation occurring at the site. Optimal temperatures for high rates of oxidation to occur range from 15-35 C; temperatures sustained above or below that range begin to decrease oxidation rates. Furthermore, there is a dependency between soil moisture content and temperature that are critical in controlling oxidation capacity. The pH of soil affects the growth of methanotrophs, with the optimal growth is found to range between pH levels of 5 to 7.5 as acidic soil can be detrimental. It is significant to note that there are differing scientific findings regarding both independent and inter-dependent environmental factors and how each variable affects methane oxidation.

The complexity of the various environmental factors and their various roles in methane oxidation make it difficult to isolate and enhance the methane oxidation process. In recent years, there have been advances in research regarding enhancing landfill methane oxidation; however, implementing some of these technologies are have economic constraints. Bioreactor systems, albeit expensive to implement, is a new technology where low-pressure air is injected into landfills to speed biodegradation and maximize oxidation while minimizing LFG emission through a gas-extraction system (Hrad, 2012). Alternatively, a more economical solution to implement is a cover system, wherein a layer of soil is spread over the landfill site. Cover systems allow for vegetation growth as well as protect the lining system that is blocking external contamination. Alternatively, cover systems enhance methane oxidation through maintaining water soil balance by preventing oversaturation from rainwater. To optimize oxidation, porous soil texture is utilized in cover systems to account for the need for O_2 and CH_4 transference (Rachor, 2010). To maximize cover soil porosity, installation and management must be treated delicately to avoid compaction, which in turn will degrade porosity. Although a large advancement in methane mitigation, cover systems do not account for lateral LFG emissions; therefore, it is recommended to apply both aeration and cover systems simultaneously.

Although advances in landfill technology are producing promising results concerning methane emissions, the options remain unattainable to under-resourced countries. Currently, landfill classifications can be distributed into three subgroups dependent upon the level of economic development of the country of origin. These subgroups are defined as follows: 1. Semi-controlled and controlled dumps without liners and lack management systems for LFG and leachate treatment. 2. Engineered/controlled landfills with operational solutions that mitigate landfill impacts on the environment. 3. Sanitary landfills, that go beyond engineered landfills, to incorporate a strategic closure plan with leachate (liquid)treatment and LFG burning with the possibility of energy recovery (Pawlowska, 2006). Current U.S. and European strategies incorporate subgroups two and three into their waste management designs as well as promoting waste mitigation through composting and reuse. Lower-Income countries still rely on subgroup one with limited waste management regulations, which lack gas-extractions, cover systems, nor liners to prevent leakage of leachate and landfill gases. These expansive dumps have raised global concerns for public health risks and the demand for immediate remediation to circumvent LFG emissions and pollution runoff (World Bank Group, 2018).

The future of landfills is beholden to economic constraints; however, research and technological innovations continue to develop possibilities for the future. These innovations are predominantly being driven and implemented at the local level through curbing the amount of waste through waste mitigation strategies and biofuel generation through gas extraction of methane. For example, the city of San Francisco has led impressive efforts to become a zero-waste city, which means sending absolutely nothing to landfills or incinerators. Through a strict fining system, the city penalizes citizens who do not meticulously participate in composting and recycling. The city's efforts have been fruitful, with 80% of their waste diverted from landfills, and packaged for recycling or composted and sold to local agriculture businesses (EPA, 2019). Beyond mitigating waste and biofuel production, there is ongoing research around the future of landfill mining. Landfill mining entails excavating a landfill to extract precious metals and materials to redistribute back into the economy. An important byproduct of excavating a landfill would be the promotion of oxidation through the introduction of oxygen and leachate circulation. However, landfill mining remains controversial due to public health risks as well as the uncertainty of revenue gains due to the current abundance levels of metals that are readily available in the existing business structure (Krook, 2012).

In summary, landfills are the third-largest generators of methane (CH_4), a greenhouse gas that can create complex public health complications concerning the release of bioaerosols and carcinogenic compounds as well as substantial environmental implications regarding global warming and climate change. Due to landfills egregious effects on public health and the environment, researchers and leading experts are developing new technology to reduce landfill methane emissions through the exploitation of methane oxidation carried out by methanotrophs. The process of methane oxidation is highly sensitive to inter-dependent environmental factors such as soil texture, organic content, moisture content, temperature, pH, and the availability of O_2 and CH_4 concentrations. To exploit this process, technologies such as bioreactor and cover systems are implemented to enhance landfill methane oxidation. In high-income countries, leading innovations are predominantly being driven and implemented at the local level through curbing the amount of waste through waste mitigation and biofuel generation through gas extraction of methane. Although these technological advances in landfill technology are producing promising results with methane emission mitigation, the options remain economically unattainable to under-resourced countries.

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