Spring 2022

The Application of Biological Processes to Increase Energy Potential in Landfills

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The Application of Biological Processes to Increase Energy Potential and Profitability in the Municipal Solid Waste Industry – Addressing the Idea of a Circular Economy in Landfills

There has been a dramatic increase in the amount of waste that we humans have created. This has been due to population growth, an increase in industrial manufacturing, along with urbanization and modernization.[8] The number of tons of municipal solid waste entering landfills has increased from 82.5 million tons in 1960 to 146.1 million tons in 2018.[17] However, thanks to recycling, composting, and energy recovery from combustion, the percentage of solid waste going to landfills has dramatically decreased, from around 93.6 to about 65.4 percent.[17]

Solid waste is categorized based on their sources, the types of wastes produced, and their generation rates and composition.[8] The sources of solid waste include residential, industrial, institutional, construction and demolition, along with municipal services.[8] Solid wastes are further categorized based on how corrosive, flammable, reactive, and toxic they are.[8]

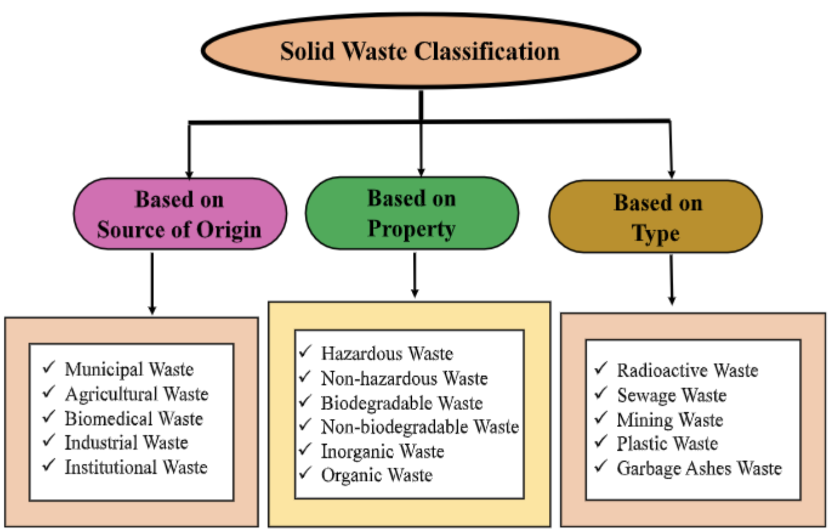

Fig. 1. Classification of solid waste.[9]

History of Landfills in the United States

What the United States used to have, and what many developing countries still have, are open dumps. In these, the trash is just piled, open to the elements and for animals to scavenge. These are not sanitary and have proven to be much smellier than landfills. Landfills are a covered disposal system, where the waste is compacted and covered with soil.[20] Now, sanitary landfills are required to be lined in order to catch leachate, which will be explained later.

Archaeological evidence suggests that landfills first emerged in 3000 BC in Knossos, Crete.[20] These were considered the first sanitary landfills as they disposed of their waste in deep holes and covered it with soil.[20] It was not until the early 20th century that trash collection was used regularly in most cities in the United States.[20] Until then, most waste was dumped in open dumps just outside the city. It was not until 1937 when the Fresno Municipal Landfill opened that compaction and covering waste with soil was used in a municipal landfill in the United States.[20] The new definition of a sanitary landfill did not develop until 1976 with the Resource Conservation and Recovery Act (RCRA).[20] This put into law that landfills have to be lined with plastic, clay, or both.[19] This followed the uncovering of both health and environmental concerns surrounding landfills and their leachate in the 1960s.[20]

Leachate is a liquid that, as it passes through the waste, picks up some of the soluble or suspended solids. Generally, it has “high concentrations of organic carbon, nitrogen, chloride, iron, manganese, and phenols.”[21] These are not the concern; the concern is the pesticides, heavy metals, and solvents that may be present.[21]

Stages of Landfills

A landfill has two life stages: operating and closed.[11] The operating stage is when there is waste being disposed of.[11] In this stage, there are more methane emissions as most of the degradation of the waste happens in the first few years after disposal.[11] When the landfill is no longer accepting waste, it is in the closed stage.[11] After a landfill closes, there is a possibility that it can continue to emit greenhouse gases for hundreds of years.[11]

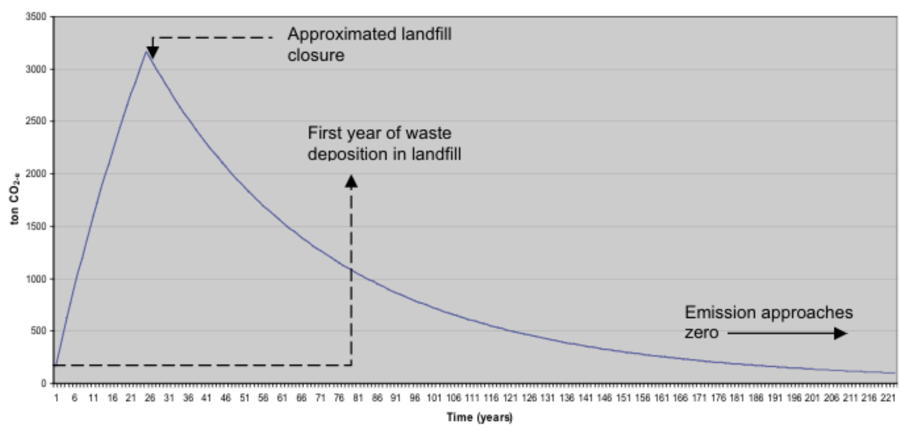

Fig. 2. The general trend of CH_4 emissions from landfills post closure.[11]

Not all greenhouse gases cause damage equally. For example, methane is a short-lived climate pollutant that causes 72 times more warming than the same amount of carbon dioxide.[12] In 2019, it was estimated that in the United States, municipal solid waste landfills contributed about 15.1 percent of methane emissions.[3] That is equivalent to the GHG emissions of about 12 million homes' energy for a year.[3] This made them the third largest emitter of methane after natural gas and petroleum systems (30%) and enteric fermentation (27%).[3] Enteric fermentation takes place in ruminant animals' digestive systems and the amount of methane produced is dependent on the microbes in the stomach.[16]

Studies suggest that 1 ton of waste generates 40 m^3 to 250 m^3 of greenhouse gases.[11] Waste decomposition changes based on waste composition.[11] This shows a "lost opportunity to capture and use a significant energy resource".[3] The amount and type of organic waste affects the gas generation, as more organic waste increases the emissions.[11] Emissions of greenhouse gases also come from the machinery from "transportation, excavation, compaction and soil spreading".[11] Estimated emissions are about 50 percent methane and 50 percent carbon dioxide, with trace amounts of other gaseous compounds.[11]

Landfills go through four phases caused by bacterial decomposition of the waste, as shown in the figure below.[3] In phase one, the aerobic phase, it starts with 80 percent of the gas released is nitrogen and 20 percent is oxygen but decreases as time goes by and carbon dioxide and hydrogen start to be released.[3] As the landfill switches in to the second phase, which is anaerobic, there is a big increase of carbon dioxide and hydrogen, big decrease in nitrogen, and the amount of oxygen released goes to zero.[3] The third phase is anaerobic, methanogenic, and unsteady.[3] In this phase, carbon dioxide decreases steadily as methane starts being released and increases steeply over this phase.[3] Nitrogen production steadily decreases and hydrogen drops to zero fairly quickly after this phase starts.[3] The fourth and final stage is also anaerobic and methanogenic, but it switches to steady production.[3] The methane production steadies to around 50 to 55%, carbon dioxide steadies to 45 to 50%, and nitrogen steadies to 2 to 5 percent.[3] The time each phase takes varies with the conditions of the landfill.[3] Different areas of the landfill can be going through different stages and may go at different rates.[3]

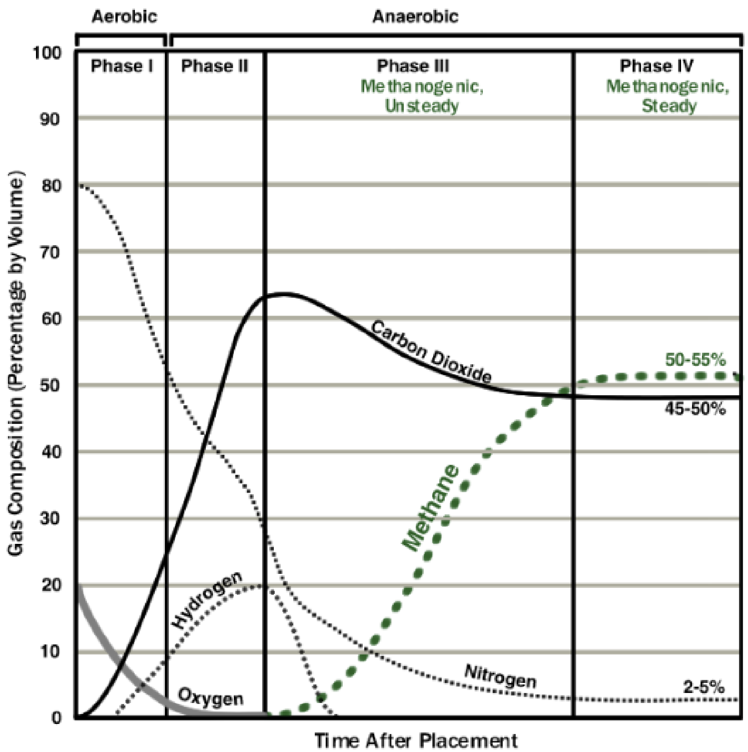

Fig. 3. Gas composition generated in landfills over each phase.[3]

Impact of Solid Waste on the Environment and Health

The improper disposal of municipal solid waste (MSW) causes pollution of not only the soil and water, but the air.[8] Waste accounts for five percent of global greenhouse emissions as methane and carbon dioxide are produced from the anaerobic decomposition of waste and wastewater.[11] Although, the estimated greenhouse gas emissions are dependent on methane, not carbon dioxide due to the biological origin and use of CO_2.[11] Landfills are the most common use for waste management and the number of landfills continues to increase as developing countries move away from open dumping.[11] The growing concern for the environment has led to "'add-on' features to landfilling such as energy recovery from LFG [, or Landfill Gas,] recovery, aerox landfills, pre-composting of waste prior to landfilling and compost capping".[11] These all have an effect on greenhouse gas emissions.

Energy Potential from Landfills[13]

A methodology of estimating LFG to energy has been created and tested in Florida.[13] This was used to help calculate the efficiency of LFG collection in seven different scenarios, including the base case.[13] Shown in the figure below, it has higher power density than other renewable energy options such as wind and hydro.

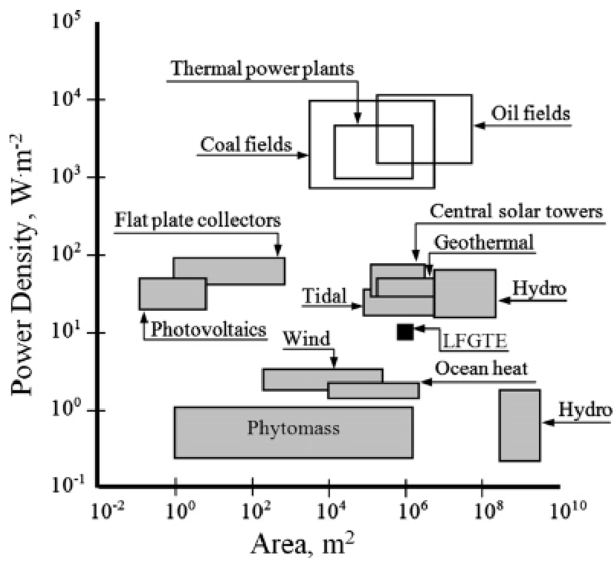

Fig. 4. Power density of LFGTE in comparison to other energy sources.[13]

The Treatment of Landfill Gas

There are three potential stages of treatment of landfill gas.[3] The primary stage of treatment is the removal of moisture.[3] During this process, the gas passes through a knockout pot, filter, and blower and can then go to a flare or to secondary treatment.[3] The removal of impurities happens during the secondary stage of treatment.[3] This uses an after cooler or other system that can help remove moisture if needed.[3] Siloxane/sulfur removal is then also done and compressed as needed.[3] The products from this stage can be used as medium-Btu fuel for arts and crafts or a boiler, or can be used to generate electricity.[3] The gas can also move forward to advanced treatment for alternate uses. In the advanced stage of treatment there is the removal of CO_2, along with N_2, O_2, and VOCs as necessary.[3] It can be compressed into high-Btu gas for vehicle fuel or go into a gas pipeline and the waste is sent to a flare or thermal oxidizer.[3]

To mitigate the greenhouse gases entering the atmosphere, the gas can be flared or combusted to recover energy.[11] This has both environmental and economic benefits. There has been an increase in landfills taking advantage of this strategy; the numbers have risen from 400 to 955 sites worldwide from 1995 to 2001.[11]

The Landfill Methane Outreach Program

The Landfill Methane Outreach Program, or LMOP, being spearheaded by the EPA has increased the number of landfills in the United States that are utilizing the gas that they produce.[3] As of March 2022 there are 541 LFG energy projects, with 474 more that are seen as good candidates for projects.[3] There are three types of these landfill energy projects: electricity projects, direct use of medium-Btu gas, and renewable natural gas.[3] Around 69 percent of these LMOP projects generate electricity that can be used onsite or sold to the electricity grid.[3] Technologies such as reciprocating internal combustion engines and turbines can be used to produce the electricity.[3] Cogeneration is also used as it generates thermal energy in addition to electricity.[3] Around 17 percent of projects directly use the medium-Btu gas produced.[3] This offsets the use of other fuels such and natural gas or coal and can be used in things such as boilers, kilns, and greenhouses.[3] This can also be used for leachate evaporation especially where other options are unavailable or costly as it makes it more concentrated for easier disposal.[3] "Current industries using LFG include auto manufacturing, chemical production, food and beverage processing, pharmaceuticals, cement and brick manufacturing, wastewater treatment, consumer electronics and products, paper and steel production, and prisons and hospitals." [3]

The final type of landfill energy project is renewable natural gas which about 14 percent produce.[3] A high-Btu gas is produced through the advanced treatment process to increase its methane content and reduce its carbon dioxide, nitrogen, and oxygen contents.[3] High-Btu gas can be used on-site as a replacement for natural gas from fossils, as pipeline gas, compressed natural gas (CNG) or liquified natural gas (LNG) or it can be transported through pipelines to other sites.[3] Additionally, it can be used to generate electricity or be fuel for vehicles.[3]

Waste to Energy Strategies

The two main technological methods of converting waste to energy are thermal and biological, which can both be broken down into further categories.[9] The thermal routes include incineration, gasification, co-gasification, and plasma gasification.[9]

The most common thermal route is the incineration of municipal solid waste. The combustion, or incineration, of waste materials that are not able to be recycled can be turned into heat, electricity, or fuel.[18] In this process, heat released from the burning of the waste converts water into steam, which then goes to a turbine generator to produce electricity.[18] The ash that remains goes to a landfill to a high-efficiency baghouse that collects the particulate matter.[18] Gas travels through this ash and removes over 99 percent of the particulate matter. [18] Those particles then go into funnel-shaped receptacles called hoppers and transported to an ash discharger.[18] From there, they are wetted and mixed with the settled ash from before and then loaded into leak-proof trucks that are covered to a landfill designed to protect against groundwater contamination.[18] The residue from the ash furnace has the possibility to be processed for the removal of scrap metals that can be recycled.[18] This is the most common thermal technology utilized.

Gasification strives to optimize the conversion of waste to fuel gas.[9] The temperature used is over 1500°C with the consideration of the pressure of the system.[9] For gasification, coal, plastics, biomass, and municipal solid waste is commonly used as feedstock.[9] Along with the creation of CO, H_2, H_2O, and CH_4, bottom ash is produced.[9] This bottom ash can be utilized in road construction as stuffing material.[9] This technique has a lessened environmental impact than that of incineration and has better energy recovery prospects.[9] In addition, it could reduce waste by 95 percent and require less cleaning than incineration.[9]

Co-gasification is an advancement of the gasification technique.[9] There is a minimal amount of tar formed, and it improves efficiency of gas formed.[9] This process uses more than one feedstock in order to accomplish this.[9] There is still a significant amount of research to be done regarding combinations of feedstocks and their effects on the gas production.[9]

Plasma gasification incorporates other types of waste like hazardous waste and tires, along with municipal solid waste.[9] This uses either a direct or alternating plasma torch as the heat source.[9] Temperatures often reach over 5000°C in this system.[9] In comparison to standard gasification, this technology has potential to increase gas production.[9]

Biological routes are dependent on microbes to break down the organic municipal solid waste.[9] These routes are preferred for waste with high organic material and high humidity content. [9] The two categories for the technology are aerobic (composting and vermicomposting) and anaerobic (anaerobic digestion).[9] Composting can help combat the odor associated with municipal solid waste (MSW) as it decays.[9] It is organic material being broken down in "wet, warm, oxidative, and non-oxidative environments under controlled conditions".[9] Technology for this is common and cost-effective regarding the treatment of the organic portion of MSW such as dairy, vegetable, food, and slaughterhouse waste.[9]

When organic waste is broken down by microbes in the presence of oxygen, it is aerobic decomposition which is what produces compost.[9] Fifty to eighty-five percent of waste could be decreased through the use of composting.[9] This would greatly reduce the load on landfills as this compost can be repurposed for fertilizer for agriculture.[9] Municipal solid waste composting has been explored using sustainable development in order to help create a circular economy to help close the loop of waste.[5] There are many advantages to this, both environmentally and economically. There is small investment required, but there is an increased speed of degradation that lessens environmental pollution.[5] Economic benefits and soil improvements and remediation also come from municipal solid waste composting.[5] There are also various disadvantages that can result.[5] There is a relatively large area that is required which can become infested with weeds.[5] Those weeds or invasive species can be spread to other areas if the fertile soil is used in other areas.[5] Biological air pollution, or bioaerosols, are also being produced and released.[5] Bioaerosols are fine particles varying in size that become suspended in the air and are either from a biological source or will affect a biological organism.[25] These particles can contain "bacteria, fungi, organic and inorganic particulates, toxins, and viruses."[25] Also with composting, there are still greenhouse gases emitted as the organic matter is broken down.[5]

Co-composting uses a mix of two or more raw materials to improve the composting process.[9] A suitable bulking agent is added to improve the rate of degradation by improving the activity of the aerobic bacteria.[9] It can be used in reclamation of soils that have been degraded from crops or contaminated soils or sediments.[9] With proper use, a mix of soils and organic waste can help restore soil structure and fertility, and help remediate degradation.[9]

Vermicomposting helps restore soil in an eco-friendly manner using microorganisms, red worms, white worms, and earthworms to change the biochemical structure of the organic waste.[9] There are three stages, which include mixture, digestion, and maturation.[9] The first stage, mixture, includes the decomposition of the waste by the bacteria and worms.[9] The temperature needs to be around 15°C for at least 2 to 5 days and the energy generation raises the temperature to around 50°C.[9] Digestion is the next stage in which fungi, actinomycetes, and earthworms degrade semi-complex compounds into substrates.[9] For this, the temperature needs to be around 60°C for around 10 to 30 days.[9] The final stage is maturation, also known as the cooling stage, which takes about 10 to 20 days for the complex compounds to degrade into substrates.[9] This can be used in sustainable agriculture as it follows the guidelines. It can also be a great fertilizer as it contains things such as micro and macronutrients, phosphate solubilizing bacteria, nitrogen-fixing bacteria, and plant growth hormones.[9]

Anaerobic digestion happens when organic waste is broken down by microbes in the absence of oxygen.[9] This is what generates biogas, a renewable energy consisting of methane and carbon dioxide that can be used in a wide variety of applications including transportation, baking, and the generation of power.[9]

The first step in anaerobic digestion is a chemical process called enzymatic hydrolysis in which complex organic polymers (lipids, carbohydrates, and proteins) are turned into soluble molecules (long chain fatty acids and amino acids).[9] A generic equation from this process is shown below, in equation 1.

$$(1)\ (C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2$$

In this stage, it is water and extracellular enzymes that are breaking up these organic polymers.[25] Extracellular, or exoenzymes, is an enzyme that is secreted by the cell and works outside the cell. Some of these enzymes include cellulase, protease, and pectinase.[25] The hydrolytic bacteria that make and secrete these enzymes typically have a fast growth rate, making this stage more efficient.[25] However, organic matter rich in lignin are rate-limiting as they are tougher for the enzymes to break down.[25] While most compounds produced need to be further broken down, some are ready to be converted into biogas.[25]

The next step is acidogenesis, also called fermentation, which is a biological process that converts small organic compounds into volatile fatty acids, CO_2, H_2, and acetic acid.[9] The equations for this stage can be seen in equations 2-4.

$$(2)\ C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2$$

$$(3)\ C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$$

$$(4)\ C_6H_{12}O_6 \rightarrow 3CH_3COOH$$

In this stage, the products from the first stage are broken down by acidogenic bacteria. Some short-chain volatile fatty acids that are formed include acetic acid and propionic acid.[25] Ammonia, alcohols, and ketones are byproducts of this process and some products such as CO_2,

H_2, and acetate are ready to be used by the methanogens at the last stage, methanogenesis. The volatile fatty acids need to be further decomposed in order to make it to the final stage.[25] Since acidogenesis is generally a very fast process, there is a risk of accumulation and toxicity in a digester.

Acetogenesis is the third step in which acetic acid is converted into acetate, CO_2, and H_2.[9] Some acetogenic bacteria that contribute include syntrophobacter wolinii, which decomposes propionate, and syntrophomonos wolfei, which decomposes butyrate.[24] Equations 5-7 below show some of what is happening in this stage.

$$(5)\ CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+HCO3^- + 3H_2$$

$$(6)\ C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

$$(7)\ CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+$$

The rate of transfer of H_2 between species can greatly influence the overall digestion rate in this stage.[25]

The fourth and final stage is where acetate, CO_2, and H_2 are converted into methane and is called methanogenesis.[9] The main product from this is methane, which is accomplished through the contributions of bacteria such as methanobacillus and methanococcus.[24] Acetophilic bacteria convert acetate into CH_4 and CO_2, while hydrogenophilic bacteria convert H_2 and CO_2 into CH_4.[25] This stage must be strictly anaerobic.[25] The methanogenic bacteria are unable to survive in the presence of oxygen.[25] The equations for this stage can be seen below:

$$(8)\ CH_3COOH \rightarrow CH_4 + CO_2$$

$$(9)\ CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$(10)\ 2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$$

Anaerobic Digesters

Organic waste, including waste from sewage and slaughterhouse operations can be diverted from landfills, or at least from being buried in landfills. Common wastes include: animal manure, food scraps, industrial organics, and sewage sludge.[23] While sending these to an anaerobic digester would increase greenhouse gas, it lessens the amount of greenhouse gas going into our atmosphere. These systems help break down these organic wastes in the absence of oxygen, which increases the amount of methane produced. This methane is contained and will not go into our environment, but will instead be used as a renewable natural gas. This can help reduce our dependence on nonrenewable energy sources such as coal and natural gas that we retrieve from fracking. Using what we already generate plenty of here in the United States, waste.

Digestate is what is left over from the anaerobic digestion process.[23] The digestate leftover from this process can also be used, so nothing will go to waste. The nutrients that could produce fertile soil if composted remain in this digestate and can be made into products such as: bedding for livestock, flower pots, soil amendments, and fertilizers.[23] This digestate can be dewatered in order for use as livestock bedding or producing biodegradable products such as flower pots.[23] It can also be directly applied to land and “incorporated into soils to improve soil characteristics and facilitate plant growth.”[23] Digestate can be bagged and sold if it is further processes.[23] The last common application for digestate is the use of emerging technologies to recover nitrogen and phosphorus.[23] This can be used to make concentrated fertilizers such as magnesium-ammonium-phosphate (struvite) and ammonium sulfate.[23]

Challenges to Waste-to-Energy

While there are numerous benefits to waste-to-energy projects, there are also some challenges. Insufficient waste recovery and recycling techniques can hinder energy production.[9] This is generally due to the general public as waste is not sorted. Waste is more prevalently sorted by companies and industries. Right now, there is some funding to get these projects started, but not enough for every landfill site to invest in these technologies. There is also a lack of awareness, mostly among the general public. It is evident in environmental policies that public comment and concern have a huge impact on what gets done. More research also needs to be done on the effectiveness and efficiency of each technique in order to optimize gas production.

Opinion

Especially in the environmental community, there is more of a push for a more sustainable and circular economy regarding waste. The first major use for waste was combustion for energy. This energy recovery largely decreases volume going into the landfill, along with the benefit of recovering energy. It is a good option for renewable energy source, as it lessens the need for fossil fuels but it is not the best option. This technique reduces methane generation, which makes it a less desirable technique for energy recovery.[18]

The collection of landfill gas is largely utilized, especially with the growth of LMOP by the EPA. This is mainly done for the economic benefits, but the EPA funds and facilitates this program as it provides environmental benefit as well. The organics leftover cannot be used, they are just trapped among the waste.

Compost is a good environmental option, and highly utilized by environmentalists, but the gas is not collected from this process, as it is mostly carbon dioxide because of the turning and incorporation of air and oxygen into the system. While this can provide economic value, more can be done through another technique in order to create, in addition, a renewable energy source.

In my opinion, the best option right now based on my research is utilizing anaerobic digesters. It seems to have the most economic and environmental benefit. It also optimizes the use of resources as the organic matter left over can be utilized for other benefits, mostly as bedding and fertilizer to help crop production.

The diversion of organic waste reduces the load on the landfill and will therefore increase the lifespan of the landfill. It is not necessarily ideal for landfills to take up large swatches of land, but they are necessary in this time in human life where we create massive amounts of waste that we need to dispose of sanitarily. Ideally, we can reduce our waste or even reduce the waste that we are directing to be buried in these systems. While compaction definitely does help, nothing helps more than diversion.

We need to utilize this opportunity for a renewable energy source. This can be a first step in decreasing our independence on fossil fuels. We know these are limited resources on which we need to lessen our dependence. As seen in Figure 4, landfill gas-to-energy has similar energy potentials for power density per area than hydro, tidal, and wind, which are big proponents in the future of renewable energy sources. While landfill gas can seem to be slightly less appealing with a little less power density compared to hydro and tidal, and requiring more land area than wind, landfill gas has an advantage in another area, its predictability. While it is hard to predict conditions pertaining to the weather, human consumption and waste creation is very consistent, and it is actually increasing. We may as well utilize this opportunity to create a new stream of renewable gas as we optimize other renewable forms of energy. Why not make the most out of all the waste we create and lighten the load on landfills while benefiting economically as well as environmentally from it?

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