Biosolids Gasification Factsheet

Executive Summary

Increasing utilization of green energy sources, coupled with the need to meet ever more stringent environmental regulations, have driven the development of innovations in wastewater biosolids management. For many municipalities there are opportunities for the beneficial use of biosolids that have undergone a traditional biological stabilization process such as composting or anaerobic digestion, but for other municipalities there may not be obvious end users that would benefit from this type of product. In some cases, the end user may be so far away that the necessary transport of the stabilized biosolids may be completely impractical. In addition, many municipalities have understandable concerns about how their current practices of beneficial biosolids reuse (e.g., land application) will be impacted by potential future regulation of per- and polyfluoroalkyl substances (PFAS).

In recent years there has been a renewed interest in implementing thermal oxidation processes as a means to beneficially use wastewater biosolids while achieving significant weight and volume reduction. Incineration of biosolids has a long history of practice in the United States and is an effective means of reducing the weight of biosolids. Other thermal oxidation processes like pyrolysis and gasification of biosolids have not been practiced as widely, but there is emerging interest in the topic.

Pyrolysis and gasification are nonbiological thermochemical process in which volatile organic compounds (VOCs) and some carbonaceous materials in the feedstock are converted into a combustible syngas (also known as synthetic gas, synthesis gas, or producer gas) in a high-temperature, low-oxygen or oxygen-free environment, leaving behind a small amount of residual ash and char. Char consists of both inert materials and carbonaceous materials not volatilized into a gas phase. Gasification typically occurs at higher temperatures than pyrolysis, with more oxygen, and converts more of the carbon to syngas. Interest in these processes being applied to biosolids is increasing because these offer significant weight and volume reduction, a viable source of green energy, carbon sequestration, and clean emissions.

This fact sheet is intended to provide a concise summary of biosolids gasification. Gasification is the focus of this fact sheet, but many of the concepts discussed are also applicable to pyrolysis. A brief summary comparison of gasification and pyrolysis is included at the end of the fact sheet.

Gasification History

Gasification processes are not new; they have a long history in a number of different applications. In larger cities, prior to the wide availability of electricity, synthetic natural gas (or syngas) generated by gasification processes operating on coal as a feedstock was used to provide heating and lighting in cities. This gas was often referred to as town gas, producer gas, manufactured gas, or coal gas, and was distributed in a network of buried pressurized gas pipelines.

Ultimately, the practice of using syngas in city gas distribution systems faded as sources of natural gas and other fossil fuels with higher heating value were discovered and became more commercially viable. However, gasification processes for heat and energy saw a resurgence during World Wars I and II as the availability of more traditional petroleum fuel sources diminished. Transportation and farm vehicles during this time were sometimes powered by wood-chip gasifiers.

Today gasification processes are used in a variety of applications, ranging from high-efficiency wood stoves to large-scale power generation systems. A renewed interest in gasification technologies has emerged in applying the process to wastewater solids.

Gasification Fundamentals

Gasification is a high-temperature thermochemical process in which carbonaceous feedstock materials are converted from a solid state into a low heating value synthesis gas, or “syngas,” and biochar. The process shares similarities with incineration but differs in several important ways.

If incineration can be thought of as “full oxidation,” then gasification is “choked oxidation.” In a gasifier, the amount of oxygen is deliberately restricted to less than the full stoichiometric requirement for complete oxidation. Full thermal oxidation would produce an exhaust gas comprised primarily of water vapor and carbon dioxide, but the syngas produced by a gasifier is comprised of many different energetic gases including carbon monoxide, hydrogen, and methane.

The solid volatile material in the feedstock is converted to syngas, but the formation of a small amount of particulate, tars, and oils is common. Any inert solids leave the gasifier as an ash or slag. The specific configuration of the gasifier and its operation (operating temperature, oxygen supply, steam addition, etc.) will affect the performance and the resulting syngas composition and the gas treatment requirements.

Comparison with Incineration

The following summary table contrasts gasification processes against incineration.

Parameter	Incineration	Gasification
Oxygen Provided	Surplus oxygen; in excess of the stoichiometric requirement	Limited oxygen; less than the stoichiometric requirement
Sulfur Emissions	Oxidized sulfur compounds (SO_x)	Reduced sulfur compounds (e.g., H_2S,)
Nitrogen Emissions	Oxidized nitrogen compounds (NO_x)	Reduced nitrogen compounds (NH_3, N_2)
Particulate Emissions (PM)	Significant potential PM emissions without proper controls	Significant potential PM and tar emissions without proper controls
Feed Preparation Required	Mechanical dewatering or thermal drying	Drying of feed materials (~80% to >85% dry solids)
Operating Temperature	1400 °F–1550 °F	1200 °F–1500 °F (process dependent)*

*Plasma gasification processes operate at temperatures of many thousands of degrees Fahrenheit, above the melting temperature of the ash

Gasification Process Description

Dewatering and Drying

One of the primary challenges with utilizing wastewater biosolids as a feedstock material is the relatively high water content of the biosolids. To operate properly, a gasifier requires a feedstock with a dry solids content of at least 80% to 85%. Water in feedstock materials decreases their energy content because the evaporation of entrained water consumes energy. Expending energy to evaporate water in the feedstock decreases the net energy production of the gasifier.

Typical mechanical dewatering processes applied to wastewater biosolids produce dewatered solids (dewatered cake) having a dry solids content between 20% and 35% dry solids (depending on the type of dewatering equipment, the type of sludge, and the optimization of the polymer dosage).

To increase the dry solids content of the feedstock, one approach is to add other, drier feedstock materials (e.g., scrap wood, used tires, etc.) in sufficient quantities to raise the average dry solids content to an acceptable level. Of course, this approach requires a reliable supply of significant quantities of feedstock material. Another approach is to apply a thermal drying process to the mechanically dewatered biosolids to reduce the moisture content. There are a number of different biosolids dryer technologies available, and often opportunities to recover waste heat from the gasifier and/or other heat sources available to satisfy dryer energy requirements. (See also: WEF fact sheet, “Drying of Wastewater Solids.”)

Processes Occurring Within a Gasifier

The reactions within a gasifier are complex, but the majority of the physical-chemical processes can be broadly categorized as follows. All of the following processes occur simultaneously within a typical continuous steady-state operating gasifier. The following processes, which can be both endothermic and exothermic, collectively are referred to as gasification. The feedstock is subjected to the following processes as it is conveyed through the gasifier and encounters localized conditions favoring different processes:

Dehydration (Drying)

When feedstock material is first introduced to the gasifier and the heat from the other processes in the gasifier begins to heat the feedstock material, the water content of the feedstock will be driven off as steam.

Pyrolysis

The pyrolysis process—literally meaning “to break with fire”—occurs after the water has been evaporated from the feedstock materials. During pyrolysis, the combination of high temperatures and an oxygen-starved environment cause the feedstock materials to volatilize into various gaseous materials. These include low molecular weight gases as well as tars and oils. The feedstock materials that remain after pyrolysis are referred to as char.

Oxidation

Where oxygen is available in sufficient quantities to react with material in the gasifier (solid or gaseous), oxidation will occur. Oxidation is an important component of the gasification process as it produces the heat (thermal energy) required to support pyrolysis and dehydration.

Reduction

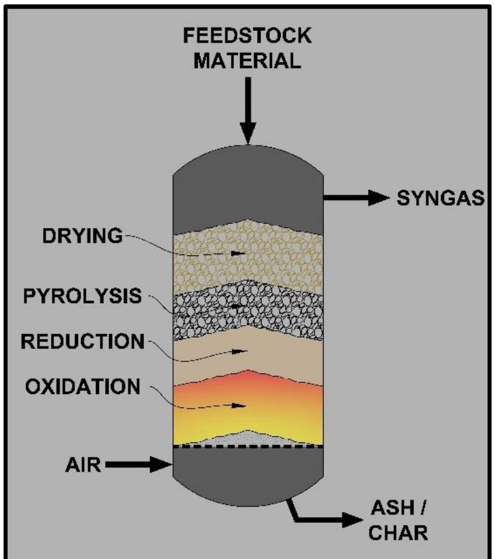
Carbonaceous materials that were not volatilized to low molecular weight gases like carbon monoxide during pyrolysis undergo further reactions to produce additional syngas. At high temperatures a number of different endothermic reactions, termed reduction reactions, convert solid materials or high molecular weight gases to low molecular weight gases. These gases can be oxidized to produce heat bioenergy for other uses, including supplemental fuel to the dewatered cake dryer.

Gasifier Configurations

A gasifier can be configured in a multitude of different ways. The following section describes four common configurations of gasifiers, but many other configurations are possible. Significant differences in gasifier performance can be achieved by varying the inputs to the gasifier and its operating conditions. Some examples include: adding steam to the gasifier, supplying air versus pure oxygen, and adjusting the gasifier operating temperature. The major differences in performance between gasifier configurations have to do with the location at which the air or oxygen is introduced to the reactor and the flow direction of the produced syngas through the reactor.

Updraft Gasifier

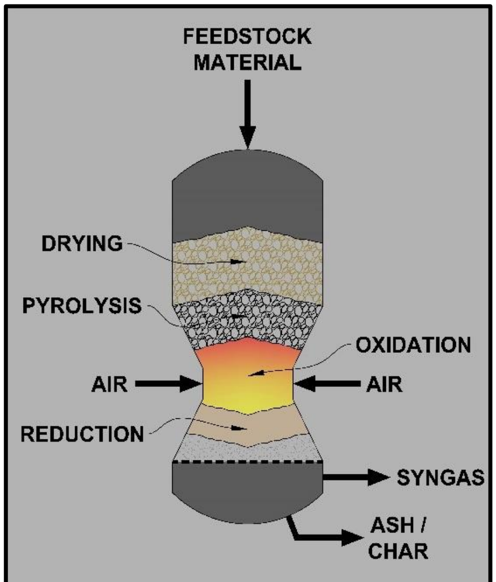
A gasifier in which feedstock material is introduced into the top of the gasifier while air is introduced at the bottom of the gasifier and travels upwards through the bed of feedstock material is termed an updraft gasifier. This type of gasifier offers a very high thermal efficiency because the heated syngas produced by the gasifier passes through the entire bed of feedstock material before exiting the gasifier. This primary downside of this configuration is that the syngas produced has a relatively high tar content.



UPDRAFT GASIFIER

Downdraft Gasifier

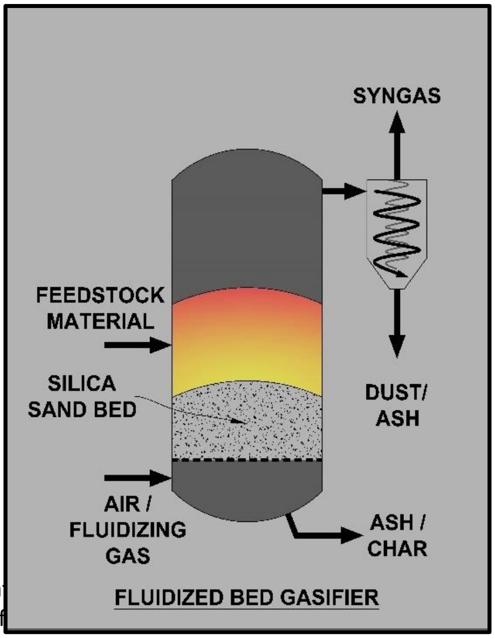
In a downdraft gasifier, the feedstock material is introduced into the top of the gasifier, but the air supplied to the gasifier is introduced at a point in the middle of the gasifier. The syngas produced is drawn down from this position and exits at the bottom of the gasifier. The primary advantage of this gasifier is that the syngas produced has a low tar content. The primary disadvantage of this gasifier configuration is the difficulty in controlling the temperature in all areas of the gasifier. This means that there is a comparatively higher potential to form slag or clinkers in a downdraft gasifier.



DOWNDRAFT GASIFIER

Fluidized Bed Gasifier

The configuration of a fluidized-bed gasifier is similar to a fluidized-bed incinerator. The feedstock material is introduced into the fluidized bed and is immediately mixed into the fluidized bed of materials in the gasifier. Air is introduced at the bottom of the gasifier along with fluidizing gases. These fluidizing gases can be steam, inert gases like nitrogen gas, or exhaust from combusted syngas. The air and fluidizing gases maintain mixing within the gasifier. Of the configurations mentioned here, the fluidized bed gasifier is the most commonly applied configuration for gasifiers operating on wastewater solids



FLUIDIZED BED GASIFIER

feedstock alone. The primary advantage of a fluidized gasifier is the ease of temperature control within the gasifier. The primary disadvantage is the relatively high tar content of the syngas produced by the gasifier.

Plasma Gasifier

A plasma gasifier operates at much higher temperatures than any of the other configurations presented here. In a plasma gasifier, arc plasma torches are applied to the mass of feedstock material, which raises the temperature of the materials to several thousand degrees. This high-temperature condition allows the gasifier to reduce even the most stable molecules in the feedstock materials to low molecular weight gases. In other gasifier configurations the temperature in the reactor must be carefully maintained below the melting point of the ash to ensure that slag or clinkers will not form, but in a plasma gasifier the temperature is so high that the inert solids in the feedstock materials leave the reactor as a molten liquid stream.

The plasma gasifier requires a significant amount of energy input to maintain the operation of the arc plasma torches, but the extremely high operating temperature allows for flexibility in the types of feedstocks which the gasifier can receive. This can include feedstocks which contain hazardous wastes and metals.

Gasifier Configuration	Advantages	Disadvantages	Feedstocks
Updraft Gasifier	• High thermal efficiency • Allows for wetter feedstocks	• Greater formation of tars • Lower generation of syngas	• Typically operated with a mix of biosolids and other feedstocks
Downdraft Gasifier	• High production of syngas • Lower tar production	• Higher formation of slag and clinkers	• Typically operated with a mix of biosolids and other feedstocks
Fluidized Bed Gasifier	• Relatively simple operational control • Allows for a range of feedstock sizes	• Greater formation of tar in syngas • Additional mixing requirements (fluidizing gases) • Greater particulate matter formation	• Can be operated on biosolids alone or in combination with other feedstocks
Plasma Gasifier	• Complete thermal destruction without tar production • Slag offers potential for metal recovery	• Operation of plasma torch consumes significant energy	• May be operated with a wide variety of feedstocks (including metallic wastes or hazardous wastes)

Feedstock Materials

Though the main focus of the information presented here is on the gasification of wastewater biosolids, gasifiers can also utilize many different carbonaceous feedstocks. Some common examples often considered are:

- Wood waste
- Scrap tires
- Waste plastics

Supplementing a gasifier’s feedstocks with other than dried sludge may require additional pretreatment measures in order to ensure that problematic materials (e.g., nails, metal shards) aren’t fed into the gasifier. Supplemental feedstocks offer the potential benefits of greater syngas output and increased flexibility in gasifier configuration. Co-gasification of biosolids and supplemental feedstock is most successful when the fixed carbon fraction of each feedstock is similar.

However, if the gasifier relies on the inclusion of supplemental feedstocks for its normal operation, the supply of supplemental feedstocks should be carefully stockpiled in order to reduce the likelihood of an interruption in gasifier operation. In addition, specific operating permits and local/state regulatory requirements would need to be considered when other feedstocks are mixed with wastewater solid

Synthesis Gas

Syngas is a common term used to describe the gas formed during the gasification process. It is sometimes referred to as a ”weak” gas because the energy content of the gas is much lower than natural gas. Unlike natural gas, which consists primarily of methane and propane, syngas is primarily comprised of hydrogen and carbon monoxide. For comparison, the heating value of natural gas distributed by natural gas utilities is roughly 1000 BTU/ft^3, whereas most syngas produced using air to facilitate gasification is expected to have heating values of 100 to 250 BTU/ft^3.

Syngas Constituents	
Energy Content (BTU/ft^3)	**100–250**
Carbon Monoxide (CO)	**30%–60%**
Hydrogen (H_2)	**25%–30%**
Carbon Dioxide (CO_2)	**5%–15%**
Water Vapor (H_2O)	**2%–30%**
Methane (CH_4)	**0%–5%**

The specific composition and quality of syngas produced by a gasifier depends on the feedstock materials; the physical configuration of the gasifier; whether the gasifier is fed with air, steam, or pure oxygen; and how the gasifier is operated. If a gasifier is fed with pure oxygen, syngas can be expected to be composed of carbon monoxide, hydrogen, carbon dioxide, water vapor, and methane.

Gasifiers fed with air can be expected to have a lower heating value due to the amount of inert nitrogen gas (N_2) present in the air fed to the gasifier. Because nitrogen gas offers no heating value and the majority of the nitrogen simply passes through the gasifier without reacting, its presence in the syngas only dilutes the heating value of the syngas. Using pure oxygen or steam eliminates this inert nitrogen gas and raises the heating value, but in the vast majority of practical applications the use of high-purity oxygen or steam introduces additional complications and hazards, making the use of air much more practical.

Syngas Utilization

The syngas produced by a gasifier can be used in a number of ways, but because the gas has a very low heating value, syngas cannot typically be used directly in conventional reciprocating piston or turbine engines for heat and power generation. In applications where syngas is sent to an engine or a turbine, the raw syngas is sometimes supplemented with a more energetic gas (e.g., natural gas) to increase the average energy content of the gas.

Another option is to apply syngas directly to a thermal oxidizer where heat can be recovered from the syngas. The high operating temperature of a thermal oxidizer may also provide a means to “polish” the exhaust gases by enhancing thermal destruction of contaminants in the syngas. The extracted heat from the thermal oxidizer can then be either used directly or can be used to generate electricity using a turbine.

Additionally, there are opportunities to refine the syngas into a source of hydrogen gas or to combine the component gases of the syngas into other types of liquid fuels using a Fischer-Tropsch process.

Emissions

One of the key advantages of gasification over incineration is the comparatively reduced concentration of contaminants in the exhaust gas. In fact, coal-fired power plants utilizing an Integrated Gasification Combined Cycle (IGCC) were found to have reduced their emissions of SOx, NOx, and particulate matter by one to two orders of magnitude (U.S. Department of Energy, 2000) after converting to gasification.

Tar Formation and Control Measures

Because oxygen is supplied to a gasifier at less than the stoichiometric requirement for complete combustion, the development of some amount of long-chain or aromatic carbon compounds is essentially unavoidable. These compounds are referred to generally as “tar” and, if they are not adequately addressed in the processing of the syngas, severe operational and maintenance difficulties can occur. Thousands of different compounds make up tar, each with their own unique physical properties. Having the proper engineering controls in place prevents damage to the equipment t processes the syngas.

Tar Control by Steam Addition

Research has shown that the addition of steam into the gasifier has the effect of shifting the production of tar materials away from refractory tars to tar materials, which can be more easily removed by other methods such as catalytic cracking (Milne et al., 1998).

Physical Removal

Tars in the syngas leave the gasifier as volatile gases, but these tars can rapidly condense into a liquid phase if the temperature of the syngas decreases. Commonly applied methods of tar removal include wet scrubbing, wet-dry scrubbing, coalescing filtration, demisters, and cold filtration. However, the physical removal of tar does not destroy the tar; it only separates it from the syngas. The separated tar materials must be dealt with appropriately to eliminate environmental hazards posed by the materials.

Tar Cracking

Of all of the processes that occur within a gasifier, combustion processes are the most energetic. Exposing tars generated during pyrolysis to the highly oxidizing environment of combustion allows the tar molecules to be broken down into smaller components, thereby removing them. It is also possible to break down tars by applying a separate thermal oxidation process. Many tar compounds can be effectively oxidized and broken down when exposed to temperatures in excess of 1000 ^{o}C.

Specialized catalytic materials can be used to lower the amount of energy required to oxidize tar and break the material into smaller components. There are many different types of catalysts available, but the catalysts are most effective while the tar materials are volatilized.

Gasification and PFAS

PFAS are a class of chemical compounds with a wide variety of applications. They are applied in everything from firefighting foams and flame retardants to food packaging materials, personal care products, and cleaning products. Several studies have reported that PFAS exposure may be associated with adverse human health effects. Studies suggest potential effects on the liver, kidneys, and the immune system, among others (Lenka et al., 2021).

As of this writing, there are currently no U.S. EPA–mandated regulations for PFAS compounds in drinking water, municipal wastewater effluent discharges, or wastewater biosolids. However, concern about the occurrences of PFAS compounds in drinking water will likely lead to future regulation and monitoring of PFAS in wastewater effluent discharges and wastewater biosolids. Thermal technologies like incineration and gasification have been shown to be capable of producing ash solids that do not contain significant amounts of PFAS.

This likely means that some of the PFAS compounds that are less thermally stable are broken down in the heat of the reactor to their elemental components. However, some PFAS compounds (e.g., flame retardants) are so stable that the temperature needed to destroy the PFAS is higher than the ash-fusion temperature of the feedstock material. These more thermally stable PFAS compounds would likely leave the thermal process intact as an air emission.

Because gasification produces an energetic syngas, there is an opportunity to couple gasification with a “second-stage” oxidation process that can operate at much higher temperatures than the temperature inside the gasifier. This higher temperature may allow for the overall process to achieve a higher degree of PFAS destruction than other thermal processes. As of this writing, data quantifying PFAS destruction for air emissions from sewage sludge gasification was still being gathered from full-scale installations. Currently, no standardized regulatory test methods for non-polymer PFAS compounds in dirty water (e.g., liquid wastewater sludge) have been established.

The U.S. EPA is currently working to develop and validate standard methods for both monitoring PFAS–contaminated air emissions and subsequent analysis of PFAS contaminants captured by those monitoring procedures. The process is complicated by the low concentration of the PFAS compounds, as well as the diversity of PFAS compounds that could be present in wastewater residuals.

Air Emissions, Regulatory Status, and Public Perception

Biosolids incinerators are subject to the U.S. EPA’s sewage sludge incineration rules promulgated under 40 CFR Part 503 (Standards for the Use or Disposal of Sewage Sludge), 40 CFR Part 60 Subpart LLLL and MMMM (Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources), and 40 CFR Part 62 (Federal Plan

Requirements for Sewage Sludge Incineration Units Constructed on or Before October 14, 2010). These rules outline emissions limits for several pollutants and apply to both existing and new incinerators. These emissions limits are reviewed and updated periodically to more and more stringent limits. Updates to the rule can sometimes impose additional operational, monitoring, and reporting requirements upon existing incinerators.

One of the reasons there has been recently renewed interest in gasification is the EPA's response to a December 2013 inquiry from a gasifier equipment manufacturer/service provider asking whether gasification was subject to the sewage sludge incineration (SSI) EG Rule. The response from the EPA was that the manufacturer's gasification process could not be classified as incineration because "no flame is applied to the sewage sludge in the gasifier, nor is a flame propagated as a result of the heating" (Messina, 2013). Thus, the gasifier was not subject to the EPA's sewage sludge incineration rules. Since 2013, the U.S. EPA has issued similar letters to gasification and pyrolysis system manufacturers.

Finally, it should be noted that as with any biosolids management program, the public's perception of the thermal treatment process and its perceived impacts to the surrounding environment can represent a significant barrier to successful implementation, even if the selected process can be demonstrated to meet all regulatory compliance objectives.

Pyrolysis-Only Thermal Processes

Pyrolysis is the precursor to all combustion and is one step of gasification. Pyrolysis is the thermochemical decoupling of VOCs and lighter fuel molecules from a solid mass at elevated temperatures in an atmosphere devoid of oxygen.

The pyrolysis process differs from gasification in several ways. The primary difference is that in pyrolysis, no carbon is oxidized in the indirect heated reactor. The lack of oxygen, moderate operation temperatures, and indirect heating configuration prevent carbon combustion to any great extent.

In a gasifier, an oxidizing agent is added (e.g., air, oxygen, steam) to oxidize a portion of the fixed carbon in the gasifier to maintain reactor temperature and enhance syngas volume and calorific value. Gasifiers are direct heat devices. This direct heat carbon oxidization produces syngas that has proven challenging to treat.

These fundamental differences between "pyrolysis only" and "pyrolysis plus gasification" have implications in terms of bioenergy produced, air emissions, and final product quality. Each of these differences is briefly discussed below.

Bioenergy Potential

Gasifiers produce more syngas at a higher calorific value than pyrolysis systems. Gasifiers can be designed to produce enough excess bioenergy to fuel 100% of the heat demand of a sludge dryer. Based on data examined to date by the author of this fact sheet, pyrolysis systems can be designed to produce about 50% to 75% of a sludge dryer's heat demand. The sludge dryer heat demand is site-specific and depends primarily on the moisture content of the dewatered cake and its volatile solids fraction.

Final Product Quality

Pyrolysis systems sequester fixed carbon in the biochar produced by the pyrolysis process. This resulting biochar product is essentially charcoal, not biosolids, and is devoid of any biological contaminants (viruses, pathogens, etc.). Gasifiers also produce a product devoid of biological contaminants; however, the carbon content of that product is much lower. The biochar utilization industry is expanding rapidly, and some refer to the high carbon biochar as "high quality" and the lower carbon product as "low quality".

Both gasifier and pyrolysis systems operating on biosolids provide similar volume reduction. Gasifiers that oxidize a large fraction of the carbon will produce a slightly lower volume of ash residuals (~5% to 10% less). Both processes concentrate nutrients in the final product. They also concentrate metals in the final product. Both processes are exempt from the U.S. EPA SSI rule requirements, but state and local air permitting is site-specific.

Impacts of Differences

The differences between "pyrolysis plus gasification" and "pyrolysis only" processes exhibit themselves in both economic and environmental considerations.

Economic Considerations

Based on data to date, including syngas fuel speciation and manufacturer-provided heat and material balances, a gasification system can be designed to furnish 100% of the heat demand of a well-designed sludge dryer. A pyrolysis system can furnish about 50% to 75% of the sludge dryer heat demand. The heat demand of a sludge dryer varies depending primarily on the dewatered cake moisture content and its volatile solids fraction.

The higher bioenergy potential of gasifiers sacrifices potential end-product beneficial uses and air emissions quality. Gasifiers produce more ash and less carbon in the final product. Pyrolysis systems sequester nearly 100% of the feedstock carbon in the biochar final product. As of this writing, at least two pyrolysis vendors are offering to sign long-term agreements to remove all biochar from the producer's site. One vendor is currently offering \$10 to \$20 per ton of biochar. Research on the beneficial uses of biochar is ongoing and includes substituting or supplementing carbon materials for applications such as carbon black, ink production, air and water filtration, and others. The lower carbon content final product from gasifiers may not offer a similar market potential. Most biosolids incineration systems, where 100% of the carbon is oxidized, landfill the ash product.

Environmental Considerations

Gasifiers produce more greenhouse gas emissions of carbon dioxide (CO_2) and NOx than pyrolysis systems. The increase is proportional to the mass of carbon oxidized in the gasifier ($C + O_2 = CO_2$). Pyrolysis systems also produce CO2 and NOx emissions from the combustion of auxiliary fuel. Both gasifiers and pyrolysis systems have demonstrated the ability to comply with air emissions standards imposed to date by individual states, including California Bay Area standards.

State of Technology

Both gasification and pyrolysis are old technologies and are tried and proven on select feedstocks. Some examples include pyrolysis of wood to make charcoal, and coal gasification. Pyrolysis and gasification of wood chips and other biomass feedstocks is practiced successfully worldwide. The choice of a particular thermal process technology is subject to site-specific considerations, which will drive the practical and economic viability of a selected process.

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Suggested Readings

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