Energy and Nutrient Recovery from Swine Manures

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Introduction

While the primary method of swine manure management in the United States is temporary storage followed by land application as crop fertilizer, there is increasing interest in recovering energy and nutrients from manures prior to land application. Insufficient nutrient assimilation capacity in nearby crop land, or interest in adding value to swine manure beyond the fertilizer value, are among the reasons that alternative management strategies may be sought. Producers who consider alternative manure uses will find many options available. This publication describes several energy and nutrient recovery processes currently available. Each process is explained and primary issues that a producer should consider with each process are discussed.

Objectives

- Summarize processes that extract energy from animal manures (urine and/or feces) as a mechanism to recover value from manure by providing on- or off-site energy.
- Summarize the economic feasibility of energy recovery and describe the non-economic benefits that may accompany several of these technologies.
- Summarize opportunities and approaches that enhance the ability to recover nutrients in order to avoid over-application of nutrients to cropland.

Energy Recovery: Introduction

Processes that extract energy from animal manures (urine and/or feces) have been considered as a mechanism to recover value from manure by providing on- or off-site energy. The feasibility of energy recovery from manures is tied to the energy and labor costs at the location in question, as well as to the non-economic benefits that may accompany several of these technologies (i.e., odor control). While gross energy in most animal feedstuffs varies very little, there may be large variation in the amount of energy that can be digested and utilized by animals, and hence available in the manure. For example, cellulose is undigested by non-ruminants; that and undigested carbon sources in any ration pass out of the digestive tract as a potential energy resource. Lignin in feeds will burn but is unavailable to animals, even ruminants, and is relatively unavailable to anaerobic microbes. The manure management system used also influences the energy value of manure. For example, the gross energy value of manures that have been highly diluted with water would be less than undiluted manures. This does not mean that energy recovery is not feasible with liquid manure slurries. Some energy recovery options, such as anaerobic digestion, are best suited to liquid manures.

Why Consider Anaerobic Digestion?

The anaerobic digestion of swine manure produces biogas (primarily a combination of methane and carbon dioxide) that can be burned to recover energy. Biogas produced from the anaerobic digestion of swine manure typically has a heating value of around 600 Btu / ft^3 and is composed of about 65% methane [1]. The methane contained in the biogas generated by the anaerobic digestion process can be burned as fuel to either generate electricity or to provide heat for on farm-use, or for both, which is referred to as co-generation. In addition to the potential for energy recovery, when properly operated, anaerobic digestion of manure can also provide significant odor reduction benefits when compared to traditional manure management methods.

How Anaerobic Digestion Works

Anaerobic digestion is the breakdown of organic compounds contained in manure by microorganisms without the presence of oxygen. Anaerobic degradation begins in the lower digestive tract of animals and continues in feces droppings, manure piles, and storage facilities. Anaerobic digestion involves multiple steps and several classes of bacteria. While methane and carbon dioxide are odorless, intermediate compounds formed during anaerobic digestion have odors. Because of this, if the anaerobic digestion process is disrupted and not completed odorous intermediate compounds may be emitted. Excess biogas produced is typically burned using a flare because the storage of the gas would require compression and is not typically economically feasible.

Anaerobic digesters can be divided into two basic types, suspended growth and fixed film. As the name implies, the consortium of anaerobic bacteria degrading the waste are suspended in the manure slurry in suspended growth systems. The suspended growth digester configurations most often used with animal waste include covered lagoons, mixed digesters (commonly called CSTR for continuously stirred tank reactors), plug-flow, and ASBRs (anaerobic sequencing batch reactors). The majority of anaerobic digesters used with swine manure are covered lagoons and CSTRs. Plug-flow digesters require a high solids manure (12-14% total solids) and are used extensively with dairy waste, but are not appropriate for most swine manures. While ASBRs are appropriate for swine manures, the use of this system type at the farm-scale has been very limited.

The bacteria in fixed film systems are attached to some type of support media, such as plastic pipes or other structure, where the bacteria can grow. Fixed film systems are commonly called anaerobic filters, since the waste must "filter" through the support media in the digester. The support media in fixed film animal waste digesters is designed to have large openings (usually 3 inches or greater) in order to prevent plugging these openings with manure solids. Fixed film digesters are best suited for low solids manures, like those commonly associated with flush manure management systems. Because bacteria remain attached, fixed film systems are capable of digesting greater volumes of manure per unit time than other types of digester systems, thereby reducing the size of the digester. Digestion systems can be designed to operate at ambient temperature or heated to operate at higher temperatures to increase the waste digestion rate. Biogas may be converted to energy to either heat the digester or provide some portion of the operation's energy needs.

Hydraulic retention time (HRT) refers to the time that influent material spends within a reactor, and can be computed by the following expression: $HRT = V/Q$, where V is the reactor volume (e.g., cubic feet), and Q is the flow rate into the reactor (e.g., cubic feet per day). Because HRT is proportional to reactor volume it has the largest influence on the fixed costs of a digester. Shorter HRT and higher loading rates typically decrease cost, but they also decrease the extent of VS conversion to biogas. Digester systems are often designed based on volatile solids (VS) loading rates. For example, a suggested range of loading rates for anaerobic digestion of swine wastes is 0.24 to 0.50lb VS/ft^3/d.

As a rule-of-thumb, 5.6ft^3 of methane can be generated for each pound of volatile solids (VS) destroyed [2]. For the typical finishing pig:

$$84 \text{ lb VS/finished animal} \times 50\% \text{ VS conversion efficiency} \times 5.6 ft^3 / \text{lb VS}$$
$$= \sim 1{,}760 ft^3 \text{ of methane per finished pig}$$

To get a better feel for the amount of energy that could be generated from swine manure we can estimate the amount of electricity that could be produced from the manure from a 150 lb finishing hog during a one-day period. If we burn the biogas in an internal combustion engine to generate electricity the manure from a 150lb finish hog would provide about 10 watts of continuous power. If we were producing power from swine manure by burning the biogas from an anaerobic digester in an internal combustion generator we would need the manure from ten 150 pound finish hogs to keep a 100 watt light bulb burning.

Considerations

Over the past three decades around 100 full-scale animal manure digester systems have been installed on farms in the United States. It is estimated that at least 50% of these digesters are no longer operational. However, the failure rate has deceased over time suggesting that current systems may be more reliable than earlier ones. Daily monitoring and management is essential to keep the system running. The consistent allocation of labor to manage the digester is necessary for success.

Anaerobic digestion stabilizes manure against further decomposition, reduces odorous intermediates, reduces the manure carbon content through CO_2 and methane production, and maintains most of the nutrient value of the manure (much now in bacterial cells) for land application. Ammoniacal nitrogen is increased and, if not lost to the atmosphere, is readily available for nitrification and crop uptake. Because manure nutrient value is retained, producers who are land-limited must seek additional means of removing manure nutrients.

The potential to capture and utilize biogas as an alternate energy source is a benefit of these systems. Because the manure generation rate varies over the swine life cycle, many times the power generation rate and power use rate on the farm will not match. One option is to sell excess power to the local utility. In some locations a premium rate for "green" power may be paid for this electricity and in other locations a rate far below the rate charged by the utility may be paid. In either case it should be noted that the interconnection with a utility power system can be very complicated due to issues concerning synchronization and safety. Because of these issues, many farms opt to flare biogas that is produced in excess of the farms power needs.

Thermochemcial Conversion: Why Consider Gasification or Liquefaction?

Thermochemcial processes such as gasification or liquefaction can be used to convert suitable manures into gases or liquids that can be used directly as low to medium BTU value fuels, or further processed into higher BTU value fuels.

How Gasification Works

Wastes containing organic matter can be thermochemically reformed into alternative energy sources. The thermochemcial conversion processes of gasification take place in a heated enclosure, absent of oxygen [3]. Gasification is a process where organic materials such as manures undergo oxygen deficient thermal decomposition into gases with low to medium BTU value. The primary gases produced include methane, carbon monoxide and hydrogen.

The main obstacle for converting swine manure into a suitable feedstock for gasification is moisture content [4,5]. Commonly employed waste management systems at swine facilities have a waste stream that is too wet for this system to be economically feasible. Some researches are studying scenarios where the waste management system is altered such that the waste material to undergo gasification is drier than material from traditional slurry systems [4].

How Liquefaction Works

Liquefaction is a high-pressure hydrogenation process where organic materials are liquefied in an oxygen-deficient environment. The liquefaction process converts the organic material into a tar or oil using a sequence of physical and chemical processes. Liquefaction increases the hydrogen to carbon ratio of the product (the liquid fuel) relative to that present in the manure. Unlike gasification, this process requires sufficient moisture for completion, as well as addition of a reducing gas such as H_2 or CO [3,6]. While some research on liquefaction of swine manure has taken place, currently, there are no commercial or pilot scale liquefaction facilities using animal manure as feedstock in place [6].

Considerations

While a great deal of research is currently being conducted concerning the gasification and liquefaction of animal manures into gases and liquid fuels, no full-scale use of this technology with animal waste is currently in use. Several pilot-scale operations, however are in operation. In order to be successfully gasified, swine waste slurries would require drying, or the manures would need to be collected in a relatively dry state.

Why Consider Direct Combustion?

Dry manures can be burned as a direct fuel source, or combined with other materials such as wood or coal. Fuels derived either wholly or partially from manures can be burned directly to produce heat and generate electricity. However, because swine produce relatively wet manure, this technology has not been pursued for swine wastes.

How Direct Combustion Works

Manure, in a relatively dry form, may be burnt directly as fuel. The use of manure as fuel is an ancient practice that is still utilized in many developing countries. The gross energy of manure, for burning, varies little between species and most of that variability can be explained by differences in ash content. Manure energy content is approximately 27.0Mcal in 15lb dry matter (DM). At 90% DM (air-dry), this represents about half that of coal.

Considerations

Most swine manure is too wet to consider burning. However, for systems that produce a dry manure, advantages of combustion processes include energy generation that adds value to manure, retention of nutrients (P and K) for fertilizer, reduction of storage requirements for the retained nutrients, and loss of N during the combustion process in the event that N loss is desirable.

When manure is burnt, the ash nutrients still need to be managed accountably. However, the responsibility for managing the ash and its nutrients (P and K, included) may be transferred depending on the individual arrangements between the burning facility and the livestock operation. Economics has been the single largest contributing factor to the limited burning that has occurred. However, other considerations include biosecurity implications of hauling to a centralized facility. Also, the exhaust gases need to be purified by scrubbers, cyclones and other types of high performance filters.

Energy Recovery Summary

Swine manure contains energy that can be recovered by various processes. The anaerobic digestion of manure to generate biogas is the process that is most easily adapted to liquid swine waste slurries. While the generation of electricity from biogas derived from animal manures is completely feasible, the economic feasibility of this system depends on subsidies paid for green power in many regions of the United States. The primary reason many animal producers give for operating anaerobic digesters is odor control. In many cases all of the biogas generated by these systems is simply flared.

Other energy recovery options are feasible for dry manures. Direct combustion and gasification both use solid manures as a fuel source. In the gasification process dry manures are thermochemically converted into low to medium BTU value gases that can be directly burned as fuel, or further processed into higher BTU value fuels such as ethanol. Economics of these systems have contributed to lack of widespread adoption.

Given the options available, when making a decision regarding the potential to recover energy from manure producers must weigh 1) their need for nutrient conservation, 2) their own need for energy that may be generated and their opportunities to sell excess energy, with 3) the overall economics of the various options relative to their goals and objectives.

Nutrient Recovery: Introduction

Opportunities and approaches that enhance the ability to recover nutrients will continue to gain popularity as the need to move nutrients offsite, in order to avoid over-application of nutrients to cropland, heightens.

Why Consider Struvite Recovery?

The forced precipitation and recovery of struvite ($MgNH_4PO_4{\cdot}6H_2O$) from swine manure can effectively reduce the phosphorus concentration of manure prior to land application.

How Struvite Systems (N & P recovery) Works

The forced precipitation of struvite ($MgNH_4PO_4{\cdot}6H_2O$) from swine manure slurries prior to land application can reduce soluble phosphorus (SP) levels in the manure slurries as well as offer the potential to concentrate and remove P from the system. Using this approach, the recovered P could then be transferred to cropping locations that are P deficient. Many producers who use flush waste management systems will already be familiar with struvite. In re-cycle flush systems struvite forms as a white crystalline scale on pump impellers and in pipe elbows and joints. Struvite formation in pipes is very problematic because it can block pipes completely and is very difficult to remove.

The forced precipitation of struvite has been demonstrated to reduce the soluble phosphorus content in swine manure by as much as 90% in field-scale tests on commercial swine finish operations [7] Laboratory and field tests were conducted using magnesium to force the precipitation of struvite, which converts the soluble phosphorus in swine manure to a crystalline mineral. This mineral form of phosphorus could be less prone to move with runoff water and useful as a slow-release inorganic fertilizer. In Europe and Japan, large municipal sewage-handling facilities are recovering phosphorus as struvite using full-scale systems. [8-13].

Considerations

While many researchers have investigated phosphorus precipitation in swine wastes on a laboratory scale, little work has been done to develop this process for field scale application [14]. Burns et al. [7] has shown a 90% reduction in soluble phosphorus via struvite precipitation in a 140,000 L swine slurry holding pond under field conditions. While pilot scale struvite recovery systems using swine manure have been developed, no full-scale systems are currently in use with animal manures.

Why Consider Solids Separation by Screening or Sedimentation?

Because most of the nitrogen and phosphorus in manures are associated with manure solids, the separation of these solids can be used as a nutrient recovery technique. When cropland is available nearby, often the liquid can be more readily applied to croplands through an irrigation system while the solids are spread on croplands or more easily exported off-farm than the wet product that precedes solid-liquid separation. Additionally the removal of manure solids prior to storage will reduce the organic loading rate of a lagoon or holding pond. Reduced loading improves organic matter digestion, maintains useful volume and designed retention times much longer before cleanout is necessary, and reduces odors in effluent.

How Solids Separation Works

Methods of separating or concentrating solids include evaporation, mechanical separation, and sedimentation (gravity settling) with or without flocculation. Sedimentation settling basins and mechanical separation are both widely used. The addition of chemical flocculants to enhance settling have been shown to be very effective with swine manures, but have seen little full-scale use due to cost.

Mechanical Separation. A number of solid-liquid separators are commercially available for manures. Mechanical separators are available that use static screens, vibrating screens, drag flight, drum roller, centrifugal and screw press devices to achieve solids separation in manures. It is also common to find separation units that incorporate a combination of these techniques. Mechanical separators typically range from $12,000 to over $100,000 in cost depending on unit size and complexity. Static screens and screw press separators are the two separator types most commonly used with swine manure. Most screen type separators require dilute, flushed manures with a TS content of 4% or less to operate properly. Screw press separators will operate using manures with a wider range of total solids content, but perform better with higher solids content slurries.

The amount of solids recovered using mechanical separation is highly variable depending on the type and amount of solids in the manure to be separated. Testing with dairy manure has indicated that separation efficiencies on a dry-mass basis can range from 15-60% depending on the TS content of the influent manure using the same separator [15]. It is important to note that separation efficiency with swine manures will be considerable lower than that reported for dairy manures because dairy manure contains large amounts of fiber that is easily separated.

Sedimentation. With diluted slurry (5-6% TS), approximately 60% of the solids are settleable by gravity sedimentation with 10 minutes or greater of settling time [16]. As solids content increases above 7%, removal decreases dramatically. Nutrient removals by sedimentation of a dilute stream (<2% TS) in a settling basin are less than that of TS removal; ranging from 15–45% of influent N and 1 - 20% of P with as much as 60min of settling time [17]. Thus, sedimentation, alone, is more effective than screening to remove both solids and nutrients. Addition of screening to sedimentation has been shown to have only marginal benefit compared to sedimentation alone.

Chemical precipitation. Chemicals commonly used for the purpose of particulate flocculation include $Al_2(SO_4)_3$ (alum), $Fe_2(SO_4)_3$, $FeCl_3$, CaCO3 (agricultural lime), CaO (chemical lime), $FeSO_4$, and synthesized polyelectrolytes. Polyacrylamide polymers, another choice of flocculant, are used extensively as settling agents in wastewaters from food processing and packing, paper production, sugar extraction, mine and municipal wastewaters, potable water treatment, and as soil treatments to reduce leaching and erosion by irrigation waters. Flocculants are used to coagulate and precipitate nutrients and solids through chemical reactions. As a result, removals observed are typically greater than 80% of TS, 60% of N, 80% of P and 60% of K [17]. Because of the chemistry, using flocculants removes more P than either N or K while N is removed to a greater extent using separation or sedimentation techniques. Chemical precipitation has not been widely adopted for agricultural purposes in part because they require a very dilute manure stream and require some sort of automated application. Cost of the chemicals is another inhibitor to their adoption. Solids and nutrients precipitated still need to be managed appropriately. However, as the need to move nutrients, particularly P, offsite implementation of flocculation using some of the cheaper flocculants (ag lime) available may become more widespread.

Considerations

Beyond the capital investment is the maintenance and operating costs of the separators. While gravity settling requires fewer mechanical parts, periodic and frequent emptying of settling basins is needed. Costs must be weighed against the variability in removal between mechanical separators and sedimentation.

Why Consider Composting?

Composting can be used to process manures into a stabilized organic material (compost) that can be land applied in place of manure. Because compost has been stabilized by aerobic decomposition it does not have odors and can be used in locations where manure use would be objectionable. If an appropriate market exists composting manure can be used as a value added product.

How Composting Works

While composting is not a nutrient recovery process, it has been included because it provides an opportunity to generate a saleable product (compost) from manures that contain nutrients. A significant amount of dried manure, composted manure, composted solids separated from manure, or some combination of these is bagged and sold as organic fertilizer. An example with dairy manure in California is a dairy cooperative that was set up to move manure off of large, intensive drylot dairies located in an urban area. The cooperative picks up the manure from the farm, takes it to a central location where it is processed, bagged, and marketed.

Composting is a logical way to process wet manure solids (but not slurries unless the slurry can be added to drier materials) when animal producers must create a product that easily moves off-farm and is stable enough so that suburban users or agricultural users near urban centers will want to use it. Composting, while it can be relatively economical, can be labor-intensive, and much of the most valuable constituent, N, is driven off to the atmosphere during processing. Therefore, operations usually consider the process only if marketable products that will help them remove excess nutrients, especially P, from the farm can be generated even if income does not equal processing and handling costs.

Considerations

Several advantages include the following: aerobic composting reduces volume and converts biodegradable materials into stable, low-odor end products; thermophilic temperatures of 130-160°F, achieved in this process, kill most weed seeds and pathogens. If moisture content is too high, anaerobic conditions develop and odorous compounds can be produced. Obviously, high quality compost has much greater value in horticultural and urban markets than simply assessing N, P, and K value. In addition, the capital investment for manure composting can be considerably less than other options provided that equipment to turn the compost is already available on the farm. Composting does require routine management of the piles in order to ensure complete and timely processing. While P and K remain in the finished product, and must be managed appropriately, much of the N is volatilized potentially creating a challenge in the face of air quality regulations. The bulk material needed to improve C/N ratio must be locally available for the process to be reasonably cost-effective.

Composting is a very well developed technology with thousands of full-scale installations utilizing animal manures worldwide. Much like anaerobic digestion the success of a composting system relies heavily on ensuring adequate labor is allocated to system management.

Why Consider Nitrogen Conservation (Loss reduction)?

While nitrogen conservation (or loss reduction) is not a nutrient recovery method, in the face of air quality regulations and the move towards P-based manure application, it only makes sense.

How Nitrogen Conservation Works

The most prevalent method to prevent volatilization of N is covering of manure storages. Impermeable covers are widely available from a number of manufacturers. A 1997 source estimated the average cover cost at $1.10 per square foot, installed however, more recent data suggest that this cost may be decreasing. Tearing and wind damage are the most commonly heard complaints. Manure pump out may also prove challenging. However, volatilization losses through the cover are minimal so the effectiveness of the strategy may outweigh any problems.

Manure acidification, while not often used, effectively reduces N losses. By reducing manure pH, the N is retained in manure as ammonium-N rather than volatilized as ammonia. Reductions of greater than 50% have been observed after reducing manure pH, post-excretion, by 2 pH units (from a pH of 7 to a pH of 5). Laboratory research has demonstrated similar reductions by altering the diet to reduce urine pH.

Maintaining urine and feces separate is perhaps the most effective means of reducing N loss through volatilization. Urease, excreted in the feces, breaks down urine to urea from which ammonia can be released. Preventing urease from coming in contact with urine should minimize N losses as ammonia to a minimum. While not yet implemented in the field, university research facilities are actively evaluating belt systems to accomplish segregation of urine and feces.

Considerations

Nitrogen conservation is easier to accomplish and relatively inexpensive when compared to many of the other technologies discussed. Nitrogen conservation techniques can be used in conjunction with several of the energy and nutrient recovery technologies discussed as well. An example would be the conservation of nitrogen in conjunction with phosphorus recovery from manures. The goal of recovering enough phosphorus such that the resulting manure was a balanced fertilizer in terms of crops nitrogen and phosphorus needs is made much easier if the manure N is conserved.

One of the largest factors in reducing nitrogen loss is the selection of the waste storage system. High solids slurry systems reduce nitrogen loss as ammonia when compared to anaerobic lagoons.

Why Consider Nutrient Recovery using Manure as an Aquaculture Nutrient Source ?

Swine manure can be used to provide the nutrients required to produce aquatic plants and animals. The nutrients in swine manure are converted into another product that the farm can sell using this integrated approach. Some aquatic plants have the potential to be used as livestock feed as well as a feedstuff for fish and other aquatic species.

How Aquaculture Works

The nutrients in swine manure can be used to produce aquatic plants, fish and other aquatic invertebrates. Typically plants such as algae and duckweed are produced and then either harvested and sold as a feedstuff for fish production, or used on-site as a nutrient source to produce fish, baitfish, crawfish or other marketable aquatic invertebrates in integrated production systems [18]. Swine manures have been used as a nutrient source for fish production in Asia for hundreds of years [19]. While significant research has been conducted on integrated swine wastewater treatment systems that include the production of aquatic plants and animals, these systems have not yet been implemented commercially in the United States.

Some aquatic plants have the potential to be used as livestock and poultry feed as well as a feed for fish and other aquatic species. Because aquatic duckweed plants have a fast biomass production rate and contain a relatively high nitrogen content (i.e., high protein content) there is recent interest in the U.S. in evaluating the potential of duckweed production as a means of treating swine manure. Use of algae or duckweed production as a waste treatment process works off the principle that nutrients from manure are recycled during the production of plant biomass. The biomass, then, can be harvested and used as a feed source in animal production. Duckweed can be produced in a grid-system that contains the duckweed mat in order to facilitate harvesting. Belt dewatering systems have shown promising for harvesting algae. While there has been considerable research conducted where bench and pilot-scale systems have been demonstrated to be feasible, to date, no full-scale integrated aquaculture systems are operational on U.S. swine facilities.

Considerations:

The recovery of nutrients as an additional farm product requires integrating two or more production systems and marketing additional products. Considerable dilution of excreted manure is required before use as a nutrient source in an aquaculture system. To be economically competitive, aquaculture systems require a warm climate with a long growing season. For these reasons, the greatest interest in the U.S. has occurred in the southern US where lagoon systems predominate and temperatures are warm. The primary market, to date, for aquatic plants such as duckweed has been fish farming which is relatively high-value when compared to livestock feed.

Nutrient Recovery Summary

While nitrogen conservation techniques and composting systems are well proven and have been used for years in conjunction with animal manures, many nutrient removal recovery systems, such as struvite recovery, have been developed only at the research or pilot scale. The fact that these systems are not being implemented at full-scale with animal manures reflects the economics rather than the technical feasibility of these systems. Producers need to consider the extent of nutrient recovery needed and weigh that against not only the economics but, also, the intensity of management needed to employ a strategy successfully.

Summary

Producers should recognize that manure energy and nutrient recovery systems produce residues that contain nutrient and organic matter at levels that must still be managed. While these systems can provide options that allow producers to recover valuable resources, produce a value added product, or be able to operate with less land, land application will still be required with most systems; ranging from needing the same amount of land for nutrient utilization with anaerobic digestion systems, to minimal on-site land application requirements for compost systems where all dry waste may leave the farm.

Where technologies such as anaerobic digestion and composting have been applied full-scale, a track record exists that producers should study as they consider implementing such a system on their own farm. The economic feasibility of a given system will be different depending on the type of manure management system in place (i.e. dry or wet manure) and the farm location (local electricity cost, nearness to markets for compost, etc). For other technologies such as struvite recovery and gasification, there are no full-scale farm applications to consider for guidance. In some cases there may be cost-share or incentive dollars available for the first adopters for some of these technologies.

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