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Green farming systems for the Southeast USA using manure-to-energy conversion platforms

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In the southeastern USA, livestock operations face issues with both manure management and energy. Both issues can be advanced by implementing holistic solutions to manure treatment that involve (1) resourceful energy management and (2) green farming systems. In such systems, current and emerging waste-to-energy conversion platforms can contribute to renewable energy solutions, improved crop yields, and sustained natural resources. System-component technologies can manage both wet and dry manures to provide recycled nutrients to crops while minimizing air and water quality impacts. Relative to energy, anaerobic digestion (AD) is the prevalent biochemical platform. It is a mature technology that readily processes wet manure, and it is used on many levels of sophistication throughout the globe. Thermochemical conversion (TCC) processes with smaller physical footprints are versatile, capable of handling wet and dry feedstocks to yield multiple byproducts. They need (1) manure feedstock conditioning to lessen the effects of salts, metals, and sulfur and (2) heat recovery for energy conservation. Additionally, with appropriate downstream processing, the TCC gases and bio-oils can aid in farm energy management to include liquid fuel. The TCC processes also produce a reasonably transportable, nutrient-dense biochar. While AD provides a digestate suitable for land application, wastewaters within these systems can also be treated at different stages with solids-separation and nitrogen-phosphorous recovery technologies. This cleaner effluent offers more options for its use in meeting crop water needs via irrigation. Thus, through holistic thinking coupled with dynamic agribusiness, there are significant opportunities for future livestock farming systems to improve the sustainability of natural resources including energy. [doi:10.1063/1.3663846]

I. INTRODUCTION

Agriculture, particularly the livestock sector, is a vital component of the Southeastern USA economy.[1] It is common to find more than 50% of the agricultural cash receipts for states of this region to come from livestock. Yet, this livestock sector has manure management issues that pose significant challenges to natural resource sustainability. There are health concerns related to the spread of antibiotic resistant pathogens, diminished air quality associated with odors and ammonia emissions,[2] and the potential to deliver excess nutrients to local water resources. As with all sectors of the global economy, obtaining sustainable energy supplies and reducing carbon footprints present significant challenges in the management and treatment of livestock manures. The complexity of farming systems and their agro-ecosystems requires astute attention to business details, effective energy management, and safeguarding of the

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supporting natural resources: it requires holistic solutions. Fortunately, there are existing and emerging technologies that (1) extract and recycle excess nutrients,[3–5] (2) destroy pathogenic microbes and pharmaceutically active compounds,[6] (3) produce renewable bioenergy,[7,8] and (4) create carbon and other natural resources credits.[9,10] While AD is widely used throughout the world, many of the emerging thermochemical bioenergy conversion technologies are compact and also applicable at the farm scale.[7,11,12] Depending on the specific technology, the treated manure and other byproducts may be more valuable to the farm and pose less of an environmental risk than untreated manure. The objectives of this paper are (1) to consider candidate manure-to-energy treatment technologies and (2) to present how these technologies could be employed in green farming systems.

II. WASTE-TO-ENERGY CONVERSION PLATFORMS

Two green farming systems are presented in Figs. 1 and 2 with each using a different waste-to-energy platform. One form of a biochemical conversion platform, represented by anaerobic digestion, is illustrated in Fig. 1. Thermochemical conversion technologies such as pyrolysis and/or gasification may be applied to agricultural production systems as illustrated in Fig. 2. Within these biological and thermochemical platforms are treatment processes designed to recycle nutrients, solve odor problems, decrease pollution potential, as well as convert portions of the inherent manure energy into more useable forms.[7] When making a selection of an acceptable conversion process, it is important to consider both availability and quantity of the feedstock, the feedstock characteristics, products (e.g., biogas, bio-oil, char), and economics.[7,13,14] For the case of manure management (Figs. 1 and 2), the final end products from each conversion process can be placed into three main groups: soil amendments; transportation fuels; heat and power generation.[11,13,15]

Biochemical conversion processes are defined by the U.S. Department of Energy as the use of living organisms or their products to convert organic material to fuels.[16] These conversion processes can utilize both aerobic and anaerobic as well as photosynthetic microorganisms, in single or multiple processes, to produce gaseous and liquid fuels. The slurry-phase residual byproduct (digestate) from these biological processes is normally nutrient-rich with potential for use as a fertilizer and soil conditioner in agriculture. In manure management, the biochemical

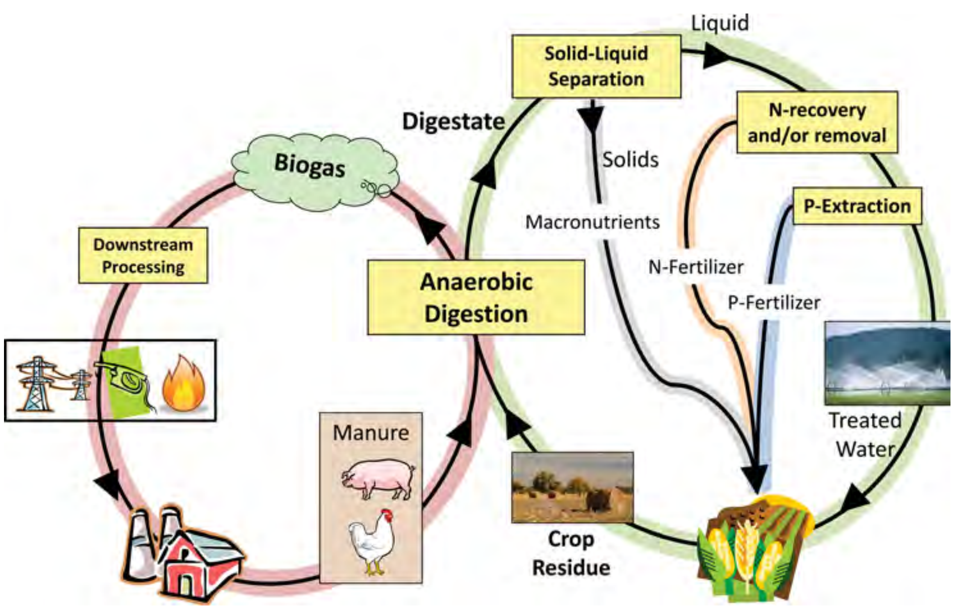

FIG. 1. Biochemical conversion-based green farming schematic using anaerobic digestion.

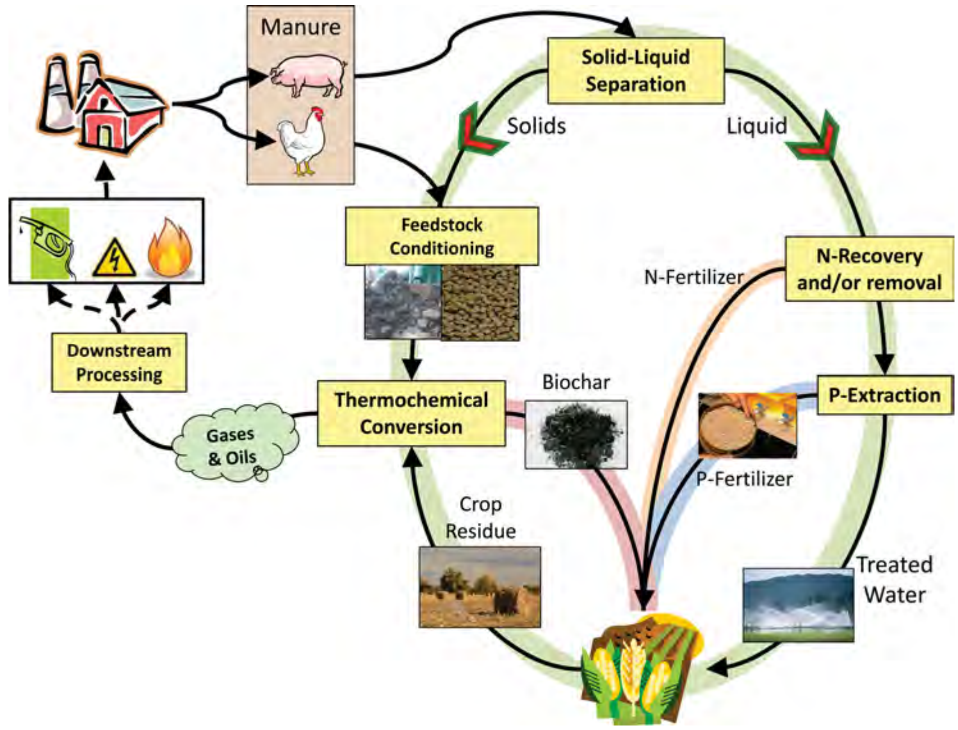

FIG. 2. Thermochemical conversion-based green farming schematic.

platform has been dominated by anaerobic digestion with full-scale production of combustible biogas often utilized to produce heat, hot process water, and electricity.

The thermochemical platform is a thermal conversion of biomass physically breaking the bonds of organic matter and reforming these intermediates into non-condensable gas, hydrocarbon-rich bio-oils, and/or a charcoal residual.[11,13,17] Thermochemical conversion processes include combustion, pyrolysis, gasification, and liquefaction. Combustion of manure yields heat that must be used immediately; thus, this method does not provide a storable energy byproduct. As such, pyrolysis and gasification have been the focus of much research largely due to their product versatility. Liquefaction is of interest due to its ability to treat more aqueous and higher moisture content manures like those from swine and dairy flush systems without the need to remove excess water first.[11,18] Regardless, either conversion platform incorporated into a green farming system provides pathogen reduction, renewable energy production, greenhouse gas emission reductions, and increased nutrient recovery efficiency.[11,12,15,19,20]

A. Anaerobic digestion

Anaerobic digestion (AD) involves the breakdown of complex organic wastes by a community of anaerobic microorganisms to produce biogas chiefly consisting of methane (CH_4) and carbon dioxide (CO_2). The AD process occurs in three main stages—hydrolysis, fermentation, and methanogenesis. During hydrolysis the complex compounds are broken down into soluble components. Thus, they are readily available for fermentative bacteria (acidogenic and acetogenic) to convert into alcohols, acetic acid, other volatile fatty acids (VFAs), and off-gas containing H_2 and CO_2. Then, methanogens metabolize these intermediate products into primarily CH_4 (60%-70%), CO_2 (30%-40%), and other associated gases. The biogas production rate is sensitive to changes in influent characteristics and process variables: pH, temperature, organic loading rate (OLR), and hydraulic retention time (HRT). These variables must be controlled in order to maximize biogas production. Anaerobic digestion is a mature technology with well developed, commercial digesters that maximize biogas production and waste utilization.[7,15]

Anaerobic digestion is widely used in EU countries particularly Denmark, Germany, Austria, and Sweden. In the EU, the 1970s saw the emergence of farm-scale biogas plants. Despite their simple design, local farmers abandoned the single-feedstock farm-scale biogas plant concept that was plagued by operational problems leading to extensive downtimes and less than sufficient biogas yields.[19–21] Since that time, the EU, particularly Denmark, has moved toward a centralized biogas plant concept where manures are transported to a central location and co-digested with other easily biodegradable organic biomass including food waste, bioenergy crops, or agricultural residues.[21] All feedstocks should be tested to make sure that they do not inhibit the digestion process. Additionally, if the digestate is destined for reuse on the farm, feedstocks should not contain heavy metals or other potentially toxic compounds. Co-digestion of dairy waste and corn silage occurs among 75%-80% of EU biogas plants.[22] Despite the trend toward centralized biogas plants, on-farm AD systems using manure as a single or co-blended feedstock are still prevalent in the EU with Germany at the forefront with more than 3500 farm-scale AD systems.[23,24] This is a stark contrast to US implementation of farm-scale AD: As reported by US EPA in October 2010, only 157 farm-scale digestors were in operation, of which 12 were centralized/regional systems processing manure from multiple farms.[25] Of all the farm-scale US digesters, approximately 22% (34 projects) are co-digesting animal manure. For developing countries, implementation of small-scale digestors serving single farms and households as waste utilization and rural energy production dwarfs developed countries with some individual country estimates, even in China, ranging from the tens of thousands to millions.[23,26–28] With so many digesters in operation, these AD designs eliminate moving parts for agitation and mixing to reduce mechanical related failures; as such, biogas efficiency is less than half of established EU biogas plants.[26,27] In contrast to EU, developing countries do not have the AD design concept utilizing devoted bioenergy crops because food production is of the utmost importance. Thus, instead of bioenergy crops, mainly crop residues are co-digested with animal manures (e.g., rice straw and seed hull, pine apple waste, coriander waste).[26] In China specifically, there are more than 2000 anaerobic digesters using animal manures as a feedstock.[29] A few of these manure anaerobic digesters are quite large. For example, a three million hen operation near Beijing operates a comprehensive anaerobic digestion system to process 212 tons of manure per day producing enough power from its biogas for the entire farm operation and for augmentation of energy for a nearby town.[30] Furthermore, a 250 000-head dairy operation in northeast China plans to build the world's largest dairy manure digestion system producing enough power to meet the average demand of some 15 000 Chinese residents.[31]

For the case of an on-farm system, biogas utilization can be grouped into three basic categories: heat and steam generation; electricity production; vehicle fuel.[28,32] In developing countries, there is minimal storage available for rural biogas production; consequently, this biogas is commonly a low pressure gas primarily used for lighting and cooking.[26,28] This leaves room for the development and implementation of compression systems and more sophisticated biogas systems to deliver pressurized biogas for gas-combustion generators for electricity. In the US, cogeneration of heat and electricity is the predominant farm-scale biogas utilization.[25] Only six of the 157 digester projects are reported to upgrade the biogas for methanol, vehicle fuel, and pipeline quality natural gas injection purposes.[25] For the EU, farm-scale generated biogas can be exported to local power plants. Alternatively, it may be upgraded to biomethane (>95% methane) for utilization as transportation fuel or in fuel cells used in onsite combined heat and power (CHP) systems where both the excess heat and electricity are sold to the public grid.[15,19,22,26,28] When targeted for these applications, the biogas must be cleaned to remove impurities like hydrogen sulfide(H_2S), CO_2, and water to increase the energy density (content) and to meet quality standards for equipment or a gas grid (Sec. II C).

For a centralized biogas facility, the economics are heavily dependent on policy incentives as well as negotiated energy contracts and/or renewable energy certificates (RECs).[15,19,23] In most instances of farm-scale AD, particularly for the US, the energy savings and potential revenue are often not enough to provide a positive cash-flow.[7] As such, grants, cost-share monies, and other subsidiary support are needed to offset some of the capital investments and encourage commercialization and regional implementation.[7,23,33]

It is important to note that while the AD process does allow for bacterial inactivation, especially in the thermophilic temperature ranges,[34] AD does not significantly reduce the volume of manure or other feedstocks. Consequently, there is still a significant volume of digestate in an AD system that must be reused or treated for disposal. The digestate contains all of the plant-readily available original nitrogen along with essentially all of the P and K. The digestate may be directly applied to land similar to traditional liquid manure land applications. However, liquid-solid separation of the digestate presents the opportunity for selective nutrient removal, thereby balancing the remaining digestate nutrients in accordance with plant requirements (Fig. 1). Thus, the nutrients are recycled increasing farm-scale independence of external inputs.

B. Thermochemical conversion

Thermochemical conversions (TCCs) are high-temperature chemical reforming processes that convert organic matter into a combination of char, synthesis gas, and highly oxygenated bio-oil. The gas is a mixture of water vapor, tars, H_2, CO, CO_2, N_2, and hydrocarbon gases. A portion of the gas condenses to form a combustible bio-oil. The unvolatilized solid residual is a combination of minerals and fixed carbon, commonly referred to as char. Once cleaned of dust, tars, metals, water, and organic acids the synthesis gases can serve as a fuel gas or bioenergy feedstock. Bio-oil also has combustible qualities allowing it to be utilized as a fuel source or bioenergy feedstock.[17] A manure-based char is a nutrient-dense material experiencing increased interest in its potential as an alternative fertilizer or soil amendment/conditioner to improve soil characteristics.[8,35–37] The TCC processes identified for converting drier wastes like poultry, turkey, and feedlot manures are pyrolysis and dry gasification.[11,38] The wetter manures traditionally from swine and dairy operations are better suited for wet gasification and liquefaction systems.[11,12,18] For each process, the distribution of end products along with their characteristics are dependent on operating temperature, pressure, heating rate, and residence time.[39,40] A summary of relevant studies are included in Table I. All of these intermediate products can find usefulness in a green farming system (Fig. 2).

Pyrolysis uses heat and a non-oxygen atmosphere to convert the organic portion of a feedstock through a series of cleavage and polymerization reactions.[40,41] The desired functionality of the end product will drive the type of pyrolysis process: Fast pyrolysis with its short residence time (seconds) and moderate temperatures (400-600°C) results in primarily a bio-oil product (up to 75 wt. % of feedstock); slow pyrolysis with longer residence times (hrs to days) and lower temperatures is utilized for targeting char production.[17,39,42] The gas by-product when slow pyrolyzing animal manures is a mixture of H_2, CO, CO_2 and lesser amounts of CH_4, water, and other light hydrocarbons. The energy content of this the gas from slow pyrolysis from of manures can vary from 40% to 77% that of CH_4 (38.3 MJ/S m^3).[8] This suggests the potential for gas utilization to range from direct burning or operation in CHP systems.

Direct liquefaction (DL) and hydrothermal carbonization (HTC) processes use aqueous feedstocks in an anaerobic atmosphere to either target bio-oil (liquid-phase) or char products, respectively. For DL, bio-oil production is targeted using a pressurized environment (5-20 MPa) in a moderate temperature range (275-350 °C); the volatile solid conversion to bio-oil can be as high as 76%.[7,18,43] The HTC process applies lower temperatures (180-250 °C) to a wet biomass feedstock under weakly acidic conditions at saturated vapor pressures (autogenic) for extended periods of time (1-72 h).[44,45] While both processes convert portions of the organic fraction into a value-added product, both also generate a gas phase that is predominately CO_2 and an aqueous phase still rich in both inorganics and organics.[7,18,44]

Gasification (both wet and dry) uses less than stoichiometric amounts of air, oxygen, or steam as a reaction medium to maximize production of noncondensable, permanent gases, CO, CO_2, H_2, and low molecular weight hydrocarbon gases.[7,46] When operated at high temperatures (800-1200 °C), dry gasification generates traces of tar (high molecular hydrocarbons) and very little char (5%-15%).[42] Wet gasification (WG) is applied to a high moisture content feedstock using pressure and temperature conditions similar to DL. However, various metallic catalysts are employed to allow for almost complete conversion of feedstock carbon into a gas mixture averaging 40% CO_2

TABLE I. Summary of results of tested thermochemical conversion (TCC) processes using livestock manure as a feedstock.

TCC process	Feedstock	Conditions	Primary product	Recovery	Reference
Direct liquefaction	Swine manure	T = 295 °C; P = 9.1 MPa, CO atmosphere	Bio-oil	70 wt. % of VS[a]	18
	Cattle manure	T = 310 °C; P = NA[b], CO atmosphere	Bio-oil	49 wt. % of VS	71
Dry gasification	Poultry litter; Feedlot manure	T = 816 °C; P = 0.1MPa[c], air atmosphere	Gas	NA	38
Wet gasification	Dairy manure	T = 350 °C; P = 21 MPa	Gas	0.67–0.81 $L\,g^{-1}$ TS	72
Slow pyrolysis	Poultry litter; swine solids (oven-dried)	T = 620 °C; P = 0.1 MPa[c]; Time = 2 h	Char	43–49 wt. % of TS	8
	Turkey litter, poultry litter, dairy manure, swine manure, cattle manure (all oven dried)	T = 350 and 700 °C; P = 0.1 MPa[c], N_2 atmosphere; Time = 2 h	Char	32–62 wt. % of TS	49
Fast pyrolysis	Poultry litter, turkey litter	T = 450–550 °C; P = 0.1 MPa[c], N_2 atmosphere	Bio-oil Gas Char	15–29 wt. % of TS 37–61 wt. % of TS 22–34 wt. % of TS	73

[a]VS = volatile solids portion, TS = total solids.
[b]Information not available.
[c]Approximation to atmospheric pressures.

and 57% CH_4.[12,47] Wet gasification of swine waste was calculated to generate the greatest positive net energy among the various livestock varieties with a net energy breakeven total solid (TS) content for the influent of 80 $g\,L^{-1}$. With flush swine waste containing a TS content of 10 to 30 $g\,L^{-1}$,[6,48] this breakeven point would require portions of the product gas energy to be used for drying the feedstock. Greater TS content up to approximately 150 $g\,L^{-1}$ (to maintain influent pumpability) would result in the WG process being a net energy generator.[12]

Implementation of TCC processes at the farm-scale is uncommon, dwarfed in comparison by AD. However, TCC processing offers a number of benefits and advantages over AD: (1) smaller physical footprint; (2) shorter residence times on the order of minutes to hours; (3) capability of handling a variety feedstocks and blends; (4) multiple complex end products; (5) high-temperature destruction of pathogens and pharmaceutically active compounds.[11,12,18] After conversion, TCC processing leaves minor residual amounts requiring disposal (compared to feedstock quantities); in the case of gasification or fast pyrolysis, the solid residual would be equivalent to the ash portion of the feedstock. It, thereby, reduces disposal charges associated with fuel, tipping, and transportation. There are, however, two serious considerations for farm-scale implementation of any TCC process: heat recovery and feedstock conditioning.

Heat recovery is an essential component to make any TCC process energy feasible. These TCC processes can quickly become net energy positive if a significant portion of the product gas or liquid stream's heat is recycled to dry and preheat the incoming feedstock. For the WG process, a double-tube heat exchanger was developed capable of recycling up to 90% of the energy used to raise the feedstock temperature.[47] Using this assumption, WG treating "straight-from-the-house" wastewater could become net energy positive using livestock wastewater with a TS content as low as 20 $g\,L^{-1}$.[12] For a swine flushed wastewater system, a WG process can have 47% more energy production of the gas compared to an AD system and become energy neutral with a heat recovery as low as 50%.[11] Granted, this moderate recovery may utilize portions of the gas as a heat source, but the process would become self-sustaining. Furthermore, any additional heat and energy recovery (beyond 50%) would allow for increased gas and bio-oil utilization for farm-specific related activities.

Livestock waste is extremely diverse in particle size, ash content, and moisture content. Thus, some type of mixing, grinding, blending, or pelletizing for uniform particle size and homogeneous feedstock will be necessary.[7,39] In the case of dry gasification and fast pyrolysis (where the feedstock is entrained in a gas-medium), uniform particle size is important to the peak temperature propagation rates. Smaller particles have a larger unit volume surface area leading to faster burnout and an increase in reactor temperature.[7,38] However, the ash content and composition of manures may adversely affect both the mechanical efficiency of the equipment (e.g., bed agglomeration and reduced peak temperatures) and the end-products' quantity and quality. Furthermore, sulfur (which could be as high as $10\,g\,kg^{-1}$ for manures[49]) has been an identified detriment to catalytic based systems.[12] These disadvantages of manure feedstocks may be avoided by homogeneously blending with agricultural residues and devoted bioenergy crops. In doing so, an additional benefit would be decreased feedstock moisture contents and the concomitant decreases in the energy required for drying the feedstock to process appropriate temperatures.[8]

C. Downstream processing

Regardless of the platform and individual technology, the energy products (e.g., biogas and bio-oil) will need to be cleaned and possibly upgraded prior to direct utilization. This would be for preventing corrosion or premature wear of catalytic or mechanical parts. Biogas and synthesis gas clean-up would include removal of water, H_2S, dust and particulate matter, and condensable oils and tars. Additional conditioning for a biomethane or fuel cell quality gas would include CO_2-removal, H_2/CO ratio adjustments, and light hydrocarbon reforming. Other inert gases may also need to be removed (e.g., N_2) to increase the energy content of the gases. This can be accomplished with molecular sieves. Typically the biogas and synthesis gas is saturated with water. Water removal can occur using cooling, compression, absorption, and adsorption technologies.[50] Hydrogen sulfide removal may be achieved with activated carbon or other chemical (e.g., NaOH) adsorption techniques. The later is only commonly used at larger regional biogas facilities because of cost as well as the safety precautions associated with handling caustic substances.[50] The dust and particulate matter can be removed via mechanical filters. Multiple technologies are available to reduce the CO_2 content: Adsorption (water, organic solvent, or chemical scrubbing); pressure swing adsorption (PSA); cryogenic separation; membrane separation.[28,50] Employing the above technologies on biogas can increase the CH_4 content from 60%-70% to 88%-97%, making it suitable for pipeline injection or vehicle fuel use.[28,50]

Adjusting the H_2/CO ratio is important for catalytic conversion of the synthesis gas to liquid fuels like methanol. Hydrogen fuel cells are another possibility. However, low temperature fuel cells require very clean hydrogen as fuel; thus, the biogas must be purified and reformed into hydrogen. High temperature fuel cells have an inherent internal reforming process; consequently, these can work directly with upgraded biogas. Using partial oxidation (POX) and steam-methane reforming (SMR) can alter the H_2/CO ratio by reforming the CH_4-containing gas stream into something customized for liquid fuel production. The SMR method is capable of producing pure H_2 gas (>99.99%).[11,51] Upon production, synthesis gas is available to synthesize clean fuels via Fischer-Tropsch technology.

Fischer-Tropsch (F-T) catalytic synthesis is one of the leading gas-to-liquid (GTL) options for generating hydrocarbon-based liquid fuels. These processes typically use metal catalysts to lower the activation energy, and the reactions take place at much lower temperatures than previous TCC processes. The F-T reaction involves catalytic hydrogenation of CO to hydrocarbon products ranging from undesirable methane to high molecular weight waxes.[52] Despite the rising popularity, the overall process efficiency is still compromised by low space-time yield, catalyst attrition, and product selectivity.[11]

Bio-oil is a dark brown heterogeneous mixture of water and oxygenated organic compounds like sugars, phenolics, and carboxylic acids.[53] The bio-oil may also contain other impurities such as fixed S, fixed N, and alkalis. The high oxygen content make bio-oils thermally unstable; however, slow pyrolysis bio-oils are more thermally stable compared to fast pyrolysis oils.[43] Bio-oils poor volatility, increased viscosity, and corrosiveness are some of the challenges limiting the range of applications.[53] The energy content of bio-oil has been reported as high as 90% of a heavy fuel oil.[18] As long as the bio-oil has consistent characteristics, bio-oils may be used in burner systems.[53] Despite the acidic nature, bio-oil may be used in industrial boilers, as long as there is a stainless steel fuel injection system.[42] Bio-oil may even be gasified to generate a synthesis gas for F-T catalytic conversion.[42] However, use of bio-oil as a transportation fuel will require removal of impurities and full deoxygenation through hydrotreating or catalytic vapor cracking.[53]

III. WASTEWATER TREATMENT

For both green farming systems (Figs. 1 and 2), the large amount of livestock waste available in the Southeastern USA is managed in a way to reduce greenhouse gas (GHG) emissions, promote sustainable energy, and effectively close the nutrient recycle loop. Parts of both platforms are well advanced and are being used on farms. Others are in developmental stages (e.g., TCC).

One of the more advanced parts pertains to the solid-liquid separation and subsequent treatment of a liquid slurry (particularly swine) [the solid-liquid separation →N-removal →P-extraction steps; Figs. 1 and 2]. A farm-scale swine wastewater treatment system has been demonstrated for use on a 5600-head finishing swine operation in Sampson County, NC.[6] This technology was an effective means of treatment alternative to open lagoons, which is a common method of handling swine wastes throughout the USA. The technology changed the way of thinking about manure management by solving multiple challenges in modern livestock production. The on-farm system used solid-liquid separation and both nitrogen and phosphorous removal processes.[6,54] This new technology produced significant direct benefits to the producers including improved animal health and productivity.[6] In addition, the new technology dramatically reduced both GHG and ammonia emissions. Replacing a lagoon with the new technology reduced GHG emissions by 97%; this reduction could allow farmers to earn additional income in emerging carbon trading markets.[9] Another potential direct benefit to producers would be trading of water quality credits (nitrogen and phosphorous) within a watershed.[10] With increasing nutrient credit programs being established throughout the USA, it may be that water quality credits will be important to livestock producers adopting new manure treatment technologies.

By treating livestock house wastewater in this manner, traditional lagoons receive no additional nutrient overloads and may begin to function so well they become blue-water-lagoons.[48] This allows more versatility in the use of the lagoons as irrigation water storage. This is an important aspect of the system for both cash crop and bioenergy production.[55] Irrigating bermudagrass with the treated effluent from such a system was found to increase bermudagrass hay yields (compared to conventional fertilizer). Furthermore, the effluent irrigated bermudagrass was (1) readily consumed as forage[56] and (2) found to have similar combustion characteristics to its conventional fertilized counterparts.[57] These findings clearly demonstrate treated livestock wastewater as not only a beneficial nutrient resource, but also a valuable water resource.

Building upon these emerging waste-to-energy treatment systems and advances are state-of-the-art nutrient extraction techniques and application (Sec. IV). By converting the livestock manures into some form of energy (e.g., biogas and bio-oils), the energy recycle loop may also be closed. With the energy content of livestock manures below that of coal, energy deficiencies may be overcome with the addition of devoted bioenergy crops or other cash crop residues irrigated with the treated water and fertilized with the recovered nutrients.

IV. NUTRIENT RECYCLING

Continued land application of manure can exceed the N and P assimilative capacity of soils and constitutes an environmental threat if these plant nutrients enter water resources via runoff or soil leaching.[58,59] An additional environmental concern with poultry and livestock production is the loss of ammonia gas (NH_3) from manure.[60] Volatilization of NH_3 from animal housing, or conventional manure storage and treatment structures contribute to unwanted ammonia deposition and air pollution.[2] Similarly, volatilization of NH_3 inside animal houses often promotes an excessive accumulation of NH_3 in air, which can negatively affect the health of both animals and workers.[61] Although increasing ventilation can lower NH_3 levels in animal houses to safe levels, it is expensive due to energy costs during winter months.[62] Conservation and recovery of both N and P is also important for animal agriculture because of the high cost of commercial N and P fertilizers. Therefore, it is important to implement best control technologies that would reduce N and P losses from confined animal operations by capturing and recovering N and P from manure.

A. Nitrogen recovery

The use of gas-permeable membranes was investigated as components of a new process to capture and recover NH_3 of manure origin from both air[4,63] and liquid effluents.[64] The basic process includes the passage of gaseous NH_3 through a microporous hydrophobic membrane, capture with a circulating diluted acid on the other side of the membrane, and production of a concentrated ammonium salt. The membranes can be tubular or flat and assembled in modules or manifolds. For recovery of NH_3 from liquid effluent, membrane manifolds are submerged in the effluent and the free ammonia (NH_3) is removed from the liquid before it escapes into the air. The concept was tested using concentrated swine manure effluents containing 300-1500 $mg L^{-1}$ NH_4-N.[64] By using the same stripping solution in 10 consecutive batches treating raw swine manure, the recovered N was concentrated in a clear solution containing 53 000 $mg L^{-1}$ NH_4-N. To capture and recover NH_3 from air, a prototype was tested using tubular membrane manifolds placed in an enclosure above, on or below the poultry litter surface.[4] The membrane technology captured and recovered 96% of the ammonia lost from poultry litter. Considering that the ammonia is captured inside the houses, this technology could help reduce ventilation and energy needs to lower ammonia levels in poultry houses. The results obtained in these studies show that the use of gas-permeable membrane technology could be an effective approach to recover NH_3 from livestock wastewater and from the air in animal houses. The final products are (1) cleaner air inside the animal houses with benefits to animal health, (2) reduced environmental emissions from livestock facilities, and (3) a concentrated liquid N that can be re-used in agriculture as a valued fertilizer.

B. Phosphorus recovery

Two novel treatment processes have been developed to recover P from manure in concentrated solid form. A wastewater treatment process was developed for removal of phosphorus from livestock wastewater.[3] The P is recovered as calcium phosphate with addition of only small quantities of liquid lime. The process is based on the distinct chemical equilibrium between phosphate and calcium ions when natural buffers are substantially eliminated. It was discovered that reduction of carbonate and ammonium buffers during nitrification substantially reduces the $Ca(OH)_2$ demand needed for optimum P precipitation and removal at high *p*H. This technology produced consistent results in pilot tests on ten swine farms and successfully demonstrated full-scale on two swine farms in North Carolina, USA.[65]

A second treatment process, called "quick wash," was developed for extraction and recovery of P from poultry litter and animal manure solids that produces a washed residue and a concentrated P material with fertilizer value.[5,66,67] The quick wash process consists of three basic consecutive steps. In step 1, a large fraction (60%-80%) of the initial total P in raw litter is selectively extracted by rapid hydrolysis reactions using mineral or organic acids when the mixture of animal waste and extracting solution reaches a *p*H of <4.5. The washed residue is subsequently separated from the liquid extract and dewatered; C and N transformation processes are inhibited by dewatering the residue. In step 2, P is precipitated by lime addition to the liquid extract forming a calcium-containing P product. In step 3, an organic poly-electrolyte is added to enhance the P concentration of the P product. The solid residue remaining after washing the animal waste with the acidic solution has a higher N:P ratio than the initial raw waste making the washed residue better balanced with respect to its N:P ratio to improve crop utilization efficiencies and avoid excess application of one nutrient—usually P.

C. Biochar utilization

Biochar is gaining increasing attention as an amendment to revitalize degraded soils, increase agronomic output, improve soil fertility, and sequester carbon. Because of these expectations, biochar fits nicely in a green farming system to close part of the nutrient cycle (Fig. 2). Alongside negligible and negative effects, reported agronomic benefits of biochar applications have been numerous.[68] The varied responses may be the result of production and post-production factors as well as the complex soil system to which the biochar was applied. Thus, there is not a "one-size-fits-all" biochar solution[68,69] to this green farming paradigm. Just as every farm has an individual manure management plan, so would their biochar characteristics need to be tailored to effectively meet the needs of farmers.

Focusing on biochar from pyrolytic processes, both manure-based and lignocellulosic biochars are predominately stable carbon aromatic structures with carbon contents ranging from 400 to 900 $g\,kg^{-1}$.[36,49] The nutrient-rich ash portion of the biochar is dependent on both the feedstock ash content and the severity of the pyrolysis process (e.g., maximum temperature and residence time). Naturally, with manures being nutrient-rich, their alkaline biochar homologues have an increased concentration of plant nutrients including P, Ca, Na, and K. As long as parent manure feedstocks heavy metal concentrations are initially below ceiling concentrations for land applications, biochar heavy metal concentrations can be permissible; however, annual loading rates should be monitored for long term repeated soil applications of manure biochars.[49] Alternatively, anywhere between 20% and 78% (mass basis) of the original N can be lost during pyrolysis[49] with the N remaining in the biochar likely to be recalcitrant, occurring in heterocyclic compounds.[70] Thus, an N-source, possibly that from the N-recovery process, would need to be applied in addition to the biochar to make a more complete nutrient supply.

Phosphorous concentrations of manure-based biochars can vary from 10 $g\,kg^{-1}$ to as high as 70 $g\,kg^{-1}$, making these types of biochars a potentially acceptable substitute for mined phosphorous fertilizer.[8,49] However, the application of these P-rich biochars should be consciously monitored as the P is readily leachable and plant available. For instance, an intensive application of poultry litter biochar (40 $Mg\,ha^{-1}$) resulted in high soil *p*H values (8-9.7) for a Norfolk loamy sand and excessively high Mehlich-1 extractable P concentrations (1280-1812 $kg\,ha^{-1}$).[36] Under these conditions, the plant available P concentrations were grossly in excess of soil plant P requirements. Furthermore, field application at this rate would be detrimental to the surrounding environment. In addition to the readily available P, other biochar constituents would need to be assessed like soluble salts and heavy metals.[49] A solution to side-step this potential problem would be to produce designer or customized biochars made from blends of manure and less nutrient-dense feedstocks like switchgrass or peanut hulls. This is yet another reason for incorporating bioenergy crops and residues in the green farming cycle (Fig. 2).These designer biochars may then be added at appropriate agronomic rates. Any high carbon, low nutrient biochars may be used at levels to impact soil characteristics.

V. CONCLUSIONS

Livestock, particularly poultry, is a huge component of the Southeastern USA economy. Yet, the management and treatment of this manure is becoming increasingly difficult via classical methods. There is also much interest in bioenergy in the Southeast USA where production of cellulosic feedstocks for energy is advantageous. Technologies and treatment methodologies are now emerging that will allow manure management and bioenergy to be synergistically advanced. While slowly emerging within the USA, anaerobic digestion where manure is a co-blended feedstock is an established treatment practice in the EU for centralized biogas production. The biogas may be utilized as a transportation fuel or in CHP systems to help increase farm energy independence. A balanced digestate may be used on crops to help close the nutrient recycle. Thermochemical conversion technologies can also convert blends of wood, grass, and livestock manure feedstocks into bioenergy. The variations of pyrolysis offer the advantage of a small physical footprint, adaptability to multiple feedstock as well as high temperature destruction of pharmaceutically active compounds and pathogens. Moreover, it produces a potentially important soil-carbon-building amendment, biochar. Other aspects of a green farming system with waste-to-energy platforms include state-of-the-art nitrogen and phosphorous removal technologies to complete the nutrient recycle. Incorporating these aspects allows for increased irrigation water storage and effective management of water resources. With astute advancement in technology, policy, and businesses models, there is significant opportunity for advanced profitable and sustainable waste-to-energy based green farming systems.

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