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Circular Economy Approaches in the Livestock Waste Area

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ABSTRACT

Many areas in the world produce more manure nutrients than available cropland can assimilate due to the agglomeration of livestock production. The development of technologies for nutrient reuse was identified as one of the five main challenges in waste management within a circular economy. More sustainable techniques using nitrogen (N) and phosphorus (P) recovery for both solid and liquid waste are important to close nutrient cycle loops in both livestock agriculture and municipal sewage systems. A circular economy in agriculture is a way of agricultural production that benefits with inputs from recycling or renewable sources. Animal manures contain many valuable materials such as ammonia, phosphorus, proteins/amino acids, compost materials, and clean water for reuse that could be extracted, recovered, and reused in a circular agriculture. The recycling and reuse of agricultural residues and concentrated products could make the most efficient use of natural sources, close the loop in nutrient cycling, and bring new income to farmers.

Keywords: Nutrient Recovery, Nutrient Re-Use, Upcycling, Waste, Manure, Organic Fertilizers, Sustainability, Concentration of Nutrients, Value-Added Products, Circular Economy

NEED FOR CIRCULAR ECONOMY APPROACH IN LIVESTOCK RESIDUES

Environmental and policy issues associated with livestock production are specific for each region; however, regardless of location, these issues generally include land application of manure and potential discharge of manure nutrients (nitrogen and phosphorus) and pathogenic bacteria to surface and groundwater; and aerial emissions of ammonia, methane, pathogens and odor. Once dominated by many small operations as part of traditional crop-livestock farms, livestock production has become highly concentrated in large operations. This development has separated animal production from crop production. Thus, the amount of manure produced often exceeds local demand for use as fertilizer.

Many areas in the world produce more manure nutrients than available cropland can assimilate. In the U.S., among all nutrients in manure, nitrogen (N) and phosphorus (P) cause the greatest environmental concern (Gollehon *et al*. 2016). In the U.S., it was estimated that 36% of the 170,000 animal feeding operations (AFO) in 2012 could not land-apply all the manure produced on the farm, resulting in farm-level excess manure containing about 868,000 metric tons of farm-level excess manure N and 388,000 metric tons of excess manure P, equal to 59% of the total recoverable manure nutrients produced on the farms (Gollehon *et al*. 2016). This illustrates linear economy processes that take starting materials and end up with products and waste streams, and the need to transform approaches to integrated processes in a circular economy that take starting materials and produce products and starting materials for other processes.

More sustainable techniques using P recovery for both solid and liquid waste are important to close the P cycle loop in both livestock agriculture and municipal sewage systems and address future P scarcity (Desmidt *et al*. 2015; Keyzer 2010). Circular agriculture is a framework that aims to close existing loops in agriculture so that natural resources can be used more efficiently.

Nitrogen is another example of the adverse effects of a linear economy of take-make-consume-dispose. Nitrogen fertilizer prices have escalated in recent years (Figure 1). The largest source of ammonia (NH_3) emissions in the U.S. is livestock production (dairy, beef, poultry, and swine), contributing 2.5 million tons per year (USEPA 2014). NH_3 emissions to the atmosphere are an environmental quality concern because they can contribute to eutrophication of surface waters and nitrate contamination of ground waters, and impair air quality (USEPA, 2014). Current practices for NH_3 production are energy intensive contributing to global warming; manufacturing one metric ton of anhydrous NH_3 fertilizer requires 861 cubic meters of natural gas (Funderburg, 2013). Therefore, developing new methods to remove and recover NH_3 from animal manure is desirable for environmental and economic reasons. Development of technologies for nutrient reuse was identified as one of the five main challenges in waste management within a circular economy (Bernal 2017). Circular economy in agriculture is a way of agricultural production that benefits with inputs from recycling or renewable sources. This recycling and reuse of agricultural residues and byproducts could not only make the most efficient use of natural sources and close the loop in nutrient cycling, but also bring added value and new income to farmers.

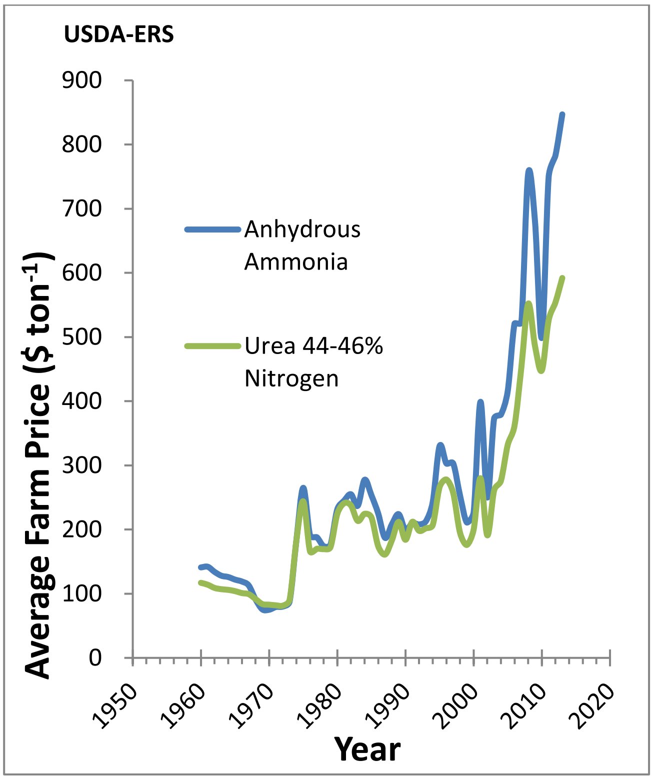

Figure 1. Fertilizer prices have escalated in recent years creating new incentives to develop technology for the recovery of nutrients from wastes (USDA/ERS, 2019).

APPROACH TO NUTRIENT RECOVERY AND WATER REUSE

Treatment can be enhanced using biological, chemical, and physical methodologies, especially in combination or as part of holistic systems (Vanotti *et al*. 2009). Figure 2 illustrates alternative approaches for removing and recovering N and P from animal manure (swine, poultry, beef, and dairy) using both on-farm and off-farm management. There are now many approaches or technologies to choose from. However, how to combine and apply them and connect their operations to the livestock value chains within an integrated agricultural system remains a major challenge for many regions.

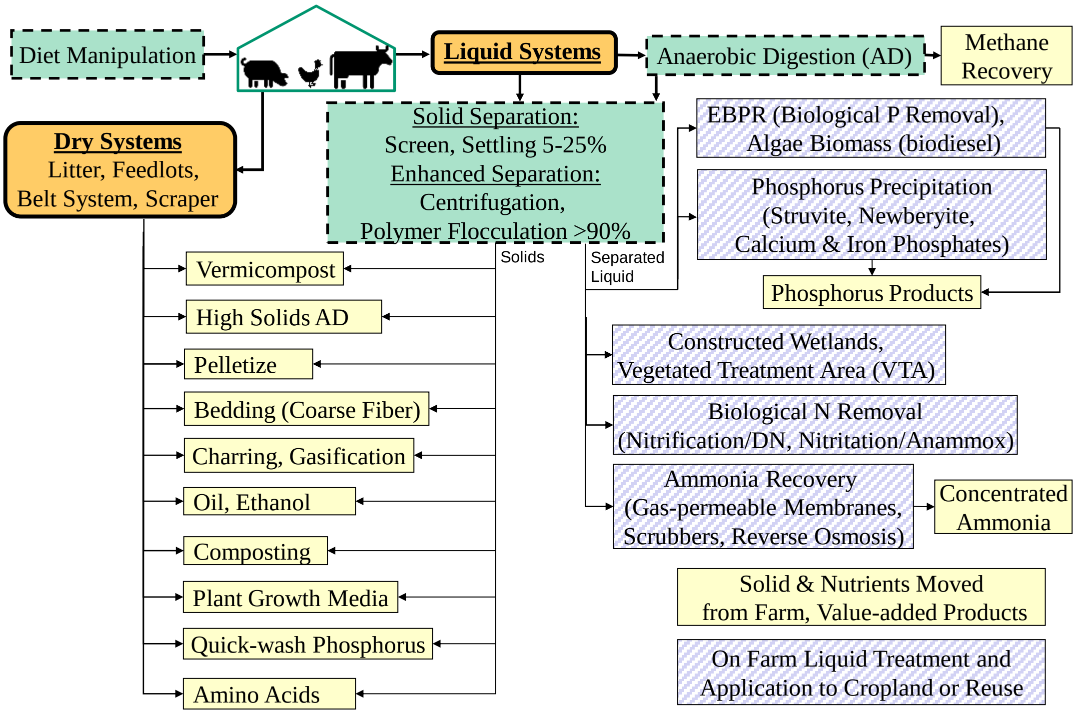

Figure 2. Schematic diagram of nutrient removal and recovery of nutrients and value-added products from manure (Vanotti *et al*. 2020).

The separation up-front in a treatment train allows recovery of the organic compounds, which can be used for the manufacture of compost materials and other value-added products or energy production. Useful products may include stabilized peat substitutes, humus, biochars, soil amendments, bio-oils, organic fertilizers, energy, quick-wash phosphorus, and proteins/amino acids. The remaining liquid can be processed to extract concentrated P and ammonia, and regenerate water for reuse in the barn for flushing, for crop irrigation, or drinking water for the livestock after further treatment. A circular economy recaptures "waste" as a resource to manufacture new materials and products (USEPA, 2022). Figure 3 shows an example of a biorefinery cascade processing system extracting several valuable materials from manure: ammonium and phosphate fertilizers, proteins/amino acids, compost materials, soilless media, and clean water for reuse.

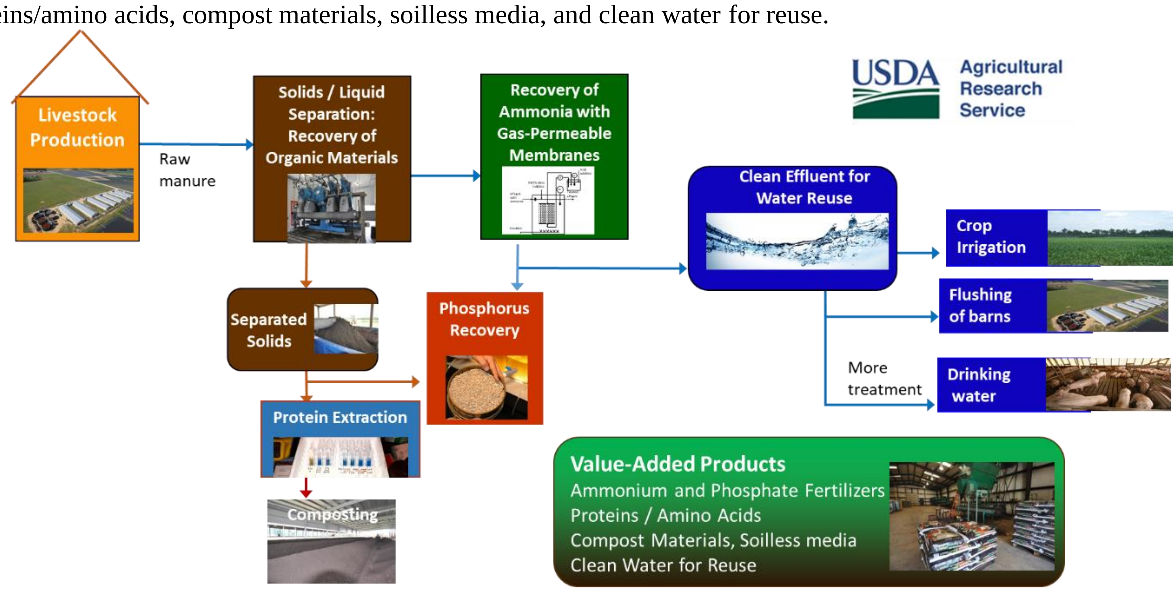

Figure 3. Biorefinery cascade processing: Recovery from manure of ammonia, phosphorus, proteins/amino acids, compost materials and clean water for reuse.

Aside from cost effectiveness/affordability, desirable characteristics of the technologies are: recovers and concentrates nutrients; produces materials with predictable nutrient concentrations; byproducts can be used directly with no need for further industrial processing other than the recovery process; ability to produce low-nutrient effluent from liquid manure stream; compatible with existing animal production facilities and manure management systems; and yields multiple additional benefits such as odor and pathogen reduction, reduce GHGs, generates energy and water for on-farm reuse, and provides other ecosystem benefits such as protection and restoration of water quality and water quality credits (Vanotti 2020).

According to scientometric analysis, the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) is the most influential research institution in the theme of "Circular Economy in Animal Waste Management" (Hollas et al., 2022): their scientists hold 17.3% of the peer-reviewed publications on the subject. This paper shows technologies developed at USDA-ARS for the recovery and reuse of valuable materials from livestock waste addressing circular agriculture needs.

Enhanced solids-liquid separation

Solid-liquid separation is a processing technology used to divide the liquid and solid fractions of manure using gravity, mechanical, and/or chemical processes. New advances over the last 15 years in equipment and flocculant applications for chemically enhancing solid-liquid separation treatment have improved the removal efficiency of solids and specific plant nutrients such as N and P (Hjorth et al., 2010; Chastain, 2019). Solid-liquid separation up-front in a treatment train allows recovery of the organic compounds that can be used for manufacture of high-quality compost materials, peat substitutes, quick-wash phosphorus and biochars (Vanotti *et al*. 2020). The polymer flocculation and screening treatment effectively removed organic nutrients (92% P and 85% N). Natural flocculants may have an important role in waste management because of the increased cost of energy and renewed interest in organic farming systems. Garcia *et al*. (2009) indicated that naturally occurring flocculants such as chitosan can be as effective as synthetic polymers for the separation of solids and nutrients from concentrated dairy manure effluents.

Value-added proteins and composts from manure solids

Composting of animal manure should be seen as a technology that adds value, producing a high-quality product focused on specific agricultural markets such as soilless media for nursery crops, orchard mulching, and organic farming (Bernal *et al*. 2009). Composting of the separated manure solids can be done in a centralized facility since it is a very specialized operation to produce high-quality materials. In this facility, the manure solids are combined with carbon rich materials such as cotton gin waste to optimize the composting process and avoid N losses (Vanotti *et al*. 2020).

Substantial amounts of proteins and phosphorus can be extracted from swine manure; 15-17% of the dry weight were proteins and 3% recovered phosphorus. A new protocol has been developed to extract proteins and phosphorus from manures. The new process uses the synergistic combination of two wastes for nutrient recovery: animal waste and fruit waste (Vanotti *et al*. 2020b). Manure contains abundant phosphorus and proteins, and fruit wastes provide sugars that produce the acids needed to extract the phosphorus and proteins.

Ammonia recovery

The recovery of N from wastes will be important in agriculture because of the high cost of commercial N fertilizers and the environmental damage of the release of reactive nitrogen. We developed new systems and methods that use gas-permeable membranes to recover significant amounts of ammonia when operated in 1) liquid manure such as lagoon and raw liquid manure (Vanotti and Szogi 2015), and 2) barns to remove the ammonia from the air (Szogi *et al*. 2014b). The new process includes the passage of gaseous ammonia through a micro-porous hydrophobic membrane and subsequent capture and concentration in a stripping solution on the other side of the membrane. For liquid applications, the membrane manifolds are submerged in the liquid, and the gaseous ammonia is removed from the liquid before it escapes into the air (Figure 4). For air applications, the membrane manifolds are suspended above the litter, and the gaseous ammonia is removed inside the barns close to the litter.

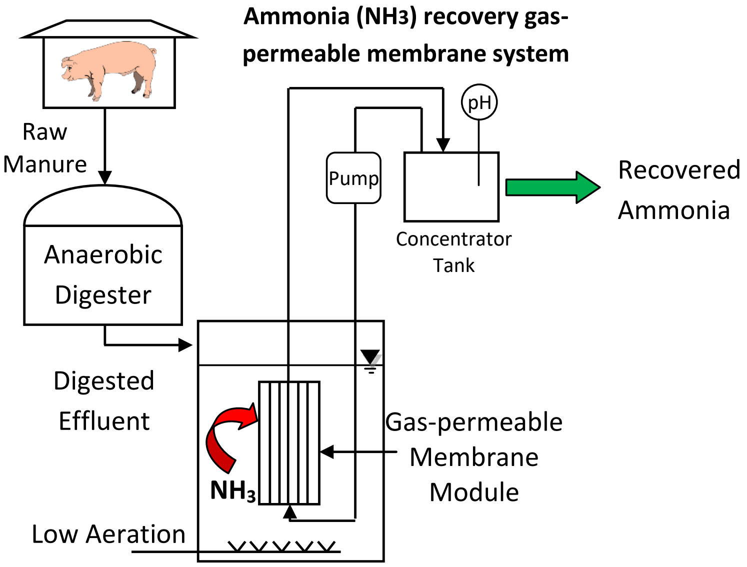

Figure 4. Enhancing recovery of ammonia from swine manure anaerobic digester effluent using gas-permeable membrane technology and low-rate aeration (Dube *et al.* 2016).

Phosphorus recovery

In animal manures, the presence of bicarbonate is an interference in the production of high-grade phosphates. Vanotti *et al.* 2005, used a biological (microbial) acidification with nitrifiers to destroy the bicarbonate and produce high-grade phosphates from swine wastewater using an alkaline-earth metal. Another method used is chemical acidification: it adds mineral or organic acids to acidify the manure before the P precipitation step with lime (Quick Wash process developed for P extraction from poultry, swine, and municipal solids, Szogi et *al.* 2014a). A third method to overcome the bicarbonate interference uses physical acidification: it adds the P precipitating compounds (calcium or magnesium) to the wastewater after the carbonate alkalinity and ammonia are substantially reduced using gas-permeable membranes (Vanotti et *al.* 2017). It was found that, when magnesium is added to wastewater with both the alkalinity and ammonia removed, the phosphates produced are very high grade (46% P_2O_5, >98% available), similar to the composition of the biomineral newberyite ($MgHPO_4$.3H2O) found in guano deposits (Vanotti *et al*. 2017).

Impact of circular economy approaches on the environment and animal production

More and more often, new treatment systems for manure combine three or four process units to meet various environmental standards and recovery targets. In North Carolina, USA, the construction of new swine farms or expansion of existing swine farms requires new waste management systems that can meet new environmental standards of ammonia and odor emissions, pathogens release, and substantial elimination of soil and groundwater contamination by nutrients (phosphorus and nitrogen) and heavy metals. A treatment system that met these multiple standards was verified at full scale in swine farms. In addition to meeting the above-mentioned environmental standards (Vanotti *et al.*, 2018), the technology was effective in reducing GHG emissions from manure management and enhancing animal productivity and health: 1. GHG emissions were reduced by 99% by replacing the anaerobic lagoon system (typically used in the USA to handle manure) with aerobic systems utilizing solids separation and composting (Vanotti *et al*. 2008); and 2. In addition, the recovery and reuse of clean water in the barns improved air quality in the barns. As a result, animal health and productivity were enhanced: feed conversion improved by 5.1%, daily gain increased by 6.1%, and mortality decreased by 47%. Overall, the farmer sold 28,100 kg more pigs per growing cycle (a 5.8% increase) (Vanotti *et al*. 2019).

CONCLUSION

Animal manures contain many valuable materials such as ammonia, phosphorus, proteins/amino acids, compost materials, and clean water for reuse, which could be reused in a circular agriculture. There is a need to develop new biorefinery cascade processing systems to extract valuable materials from manure to make the most efficient use of natural sources, to close the loop in nutrient cycling, and to bring new income to farmers.

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COMPETING INTERESTS

MBV declares no conflict of interest.