Life Cycle Assessment (LCA) as a Framework for Addressing the Sustainability of Concentrated Animal Feeding Operations (CAFOs)

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Abstract

The challenges Concentrated Animal Feeding Operations (CAFOs) directly pose to sustainability include their impact on human health, receiving water bodies, groundwater, and air quality. These challenges result from the large quantities of macronutrients (carbon, nitrogen, and phosphorus), micronutrients (sulfur and heavy metals), and antibiotics contained in the effluent from CAFOs. Technologies exist to deal with the challenges CAFOs present. We evaluate how Life Cycle Assessment (LCA) may be used to evaluate the gaps in knowledge when combining technologies currently available for dealing with the sustainability of CAFOs.

Introduction

Because concentrated animal feeding operations, CAFOs, are an economically efficient means of producing animals used in human diets, it seems likely that use of CAFOs will increase. The purpose of this paper is (1) to present the challenges of CAFOs to environmental sustainability, (2) to provide life cycle assessment (LCA) background, (3) to provide a brief review of work on LCA, CAFOs, and waste, and (4) to present technological possibilities for making CAFOs more sustainable and where knowledge gaps exist in performing LCA on the wastes CAFOs generate thus pointing towards future research.

Problems CAFOs pose

The challenges of CAFOs present to environmental sustainability include: (1) Release of high concentrations of macronutrients (carbon, nitrogen, and phosphorus) into the environment that can lead to degradation of water, air and land. The urine and feces produced at CAFOs contain large concentrations of macronutrients and heavy metals(Basset-Mens et al. submitted; Biological and Agricultural Engineering Department and Agronomic Division 1994). Degradation of water is due to algal bloom outbreaks (Balakrishnan and Eckenfelder 1969), depletion of dissolved oxygen concentrations, fish kills(Burkholder *et al.* 2004), hypoxia, and selection of flesh-eating microorganisms such as *Pfiesteria* (Burkholder *et al.* 1999). Degradation of air is due to volatilizing nitrogen (ammonia) that causes odor problems (Jackson *et al.* 2000) and can then lead to acidification of water bodies

(Moore et al. 1995). Degradation of land results from bacterial oxidation of nitrogen contained in the waste to form nitrate. Nitrate is a soluble compound that can degrade well water with potential for methemoglobinemia or blue-baby syndrome (Downs et al. 1999), and risks of colon cancer for certain subpopulations (De Roos et al. 2003).
(2) Release of large quantities of heavy metals into the environment can lead to degradation of water and land. Heavy metals are blended in the animal feed to serve as trace elements for the growth-enhancing enzymes (Wilcke *et al.* 2002). In addition, animals may be fed with activated sludge, a rich source of nitrogen, leading to biomagnification of heavy metals contained in the activated sludge (Bag et al. 1999). Relatively large (compared to background level) concentrations of aluminum (Al), manganese (Mn), boron (B), copper (Cu), cobalt (Co), and arsenic (As) are contained in animal wastes (Biological and Agricultural Engineering Department and Agronomic Division 1994)[1]. While deficiencies of many of these elements are detrimental to human health, large doses are also detrimental. Large concentrations of Al may be associated with chronic neurological disorders(Campbell *et al.* 2004), Mn with nervous system disorders (Bast-Pettersen and Ellingsen 2005; Sassine *et al.* 2002), B with fetal development problems (Lanoue *et al.* 1998; Parks and Edwards 2005), As is associated with brain developmental problems(Wasserman *et al.* 2004), and Cu, Co and As play roles in carcinogenicity(Valko *et al.* 2005).
(3) Release of large quantities of antibiotics into the environment can lead to degradation of air, water and land (Chapin *et al.* 2005). Because animals live in close proximity to one another, disease can spread very rapidly among the population. To prevent this and to promote growth, the animals are injected with large quantities of antibiotics, not all of which are metabolized within the animal (Wegener 2003). As a result, antibiotics are excreted in the urine and feces of the animals. Release of these antibiotics can lead to selection of resistant microorganisms in the wider environment, particularly in water (Campagnolo *et al.* 2002) and groundwater(Chee-Sanford *et al.* 2001). Increased numbers of antibiotic-resistant pathogens may affect human health particularly in the areas near the CAFOs (Wegener *et al.* 2000; Wegener *et al.* 1998).

Life Cycle Assessment (LCA)

A comprehensive life cycle assessment (LCA) provides a cradle-to-grave framework to assess industrial systems. This approach begins with consideration of raw materials contained within the product and ends at the point when all materials are returned to one of the three environmental sinks – the air, water, or land. A comprehensive LCA provides a framework for evaluation of all stages of a product's life from the perspective that each stage is interdependent upon another. Thus, this framework enables the estimation of the cumulative environmental impacts. LCA permits assessment of impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including these impacts, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product selection.

The steps to preparing an LCA include:

- Compilation of an inventory of relevant energy and material inputs and environmental releases (Life Cycle Inventory);
- Evaluation of the potential environmental impacts associated with identified inputs and releases (Impact Assessment); and
- Interpretation of the results to help make more informed decisions (Life Cycle Interpretation).

The product life cycle consists of those major activities in the course of the product's life-span. These will necessarily be product specific, but might include raw material acquisition, production, use, maintenance, and final disposal. Figure 1 illustrates the possible life cycle stages that can be considered in an LCA and the typical inputs/outputs measured.

One of the advantages of LCA framework is that it allows flexibility of the definition of the systems boundaries so that subsystems can be assessed. This in turn allows LCA to take a "plug-and-play" approach similar to frameworks in computer science. An LCA assessment of CAFOs would seem to be an initially daunting task. However, decomposition of CAFOs into different steps allows for a more tractable problem. This is the approach taken by other researchers (Basset-Mens *et al.* submitted; van der Werf *et al.* 2005) and the approach taken here.

Studies on LCA, CAFOs, and Waste

The literature on LCA and CAFOs is in the early stages. To date, assessment of the raising of feed for concentrated pig operations has been considered (van der Werf *et al.* 2005) and the land application of wastes from concentrated pig operations (Basset-Mens *et al.* submitted). For dairy farms, there were contradictory studies showing that intensive milk production had either more (Haas *et al.* 2001) or less (Eide 2002) than small-scale farming. It should be pointed out that these studies were in different locations and contained methodological differences.

There are two problems with the studies considering LCA and land application of the wastes from CAFOs (Basset-Mens *et al.* submitted; Eide 2002; Haas *et al.* 2001): (1) far more macronutrients (nitrogen and phosphorus) are contained in the waste than the land can process without environmental degradation; and (2) there is no consideration of the pathogens contained within the waste. For these reasons, intensive means of waste treatment should be considered for CAFOs.

Treatment of municipal waste streams is routinely handled with intensive waste treatment. One study used LCA to assess treatment of the organic fraction of municipal solid waste (OFMSW) with open composting, closed composting, anaerobic digestion + aerobic post-processing, anaerobic digestion + open composting, anaerobic digestion + closed composting, and incineration (Edelmann *et al.* 2005). This same study also used LCA to assess treatment of wastes from animal raising operations (both pig and cow) with and without OFMSW addition (Edelmann *et al.* 2005). The technologies considered included anaerobic digestion and optimized manure handling. The combinations considered were: anaerobic digestion of animal waste + OFMSW with optimized manure handling, animal waste + OFMSW without optimized manure handling, and animal waste alone. The basis for comparison was the generation of 1 TJ of electricity from the biogas produced. CH_4, N_2O, and NH_3

gas emissions had large impacts on the LCA analysis of animal wastes. Anaerobic production of biogas caused both increased ammonia mineralization and increased ammonia volatilization. Manure handling also proved to be important in the LCA analysis as the volatilization of NH3 pre- and post-digestion was important, accounting for over 50% of environmental impacts (Edelmann *et al.* 2005). The study also shows that anaerobic digestion alone may result in nitrogen overload of the land on which the post-digestion manure is being applied. The fate of the volatilized ammonia produced in the digesters was also not clear from the study's results. While the study did present an approximation of the mean value of heavy metals concentrations for OFMSW, there was none for the animal waste (Edelmann *et al.* 2005). It is should also be stressed that the heavy metals concentrations will depend heavily on dietary supplements of the animals.

Possible Solutions, Sustainability, and Future Research

In Table 1 different treatment process technologies currently available capable of treating different parts of the problem CAFOs present are shown. No single process would be capable of addressing the problems of macronutrient, micronutrient, and removal of antibiotic-resistant microorganisms.

Different combinations of these processes will thus be needed for CAFOs. While various pieces have been partially analyzed for CAFO wastes, there has not been a comprehensive effort to integrate the different pieces. Some of the work that has been performed seems contradictory, e.g., must carbon be removed from the waste stream prior to use of anammox technology. In addition to meeting the health requirements that are a minimum, the system(s) should minimize energy used (or maximize recoverable energy produced), minimize use of chemicals, minimize greenhouse gases produced (CO_2, SO_2, N_2O), and maximize recovery of utilizable materials, e.g., water, phosphate, metals, utilizable organic material. It is likely that there will be tradeoffs in these different goals that sustainability presents. Furthermore, it is also likely that one single process will not be best in every situation. An additional possibility of research is how wastes from CAFOs can be totally, partially, or not at all treated prior to addition to waste streams from industrial processes. Some industrial processes, e.g., petrochemicals, paper and pulp, lack key macronutrients that CAFO waste streams could offer.

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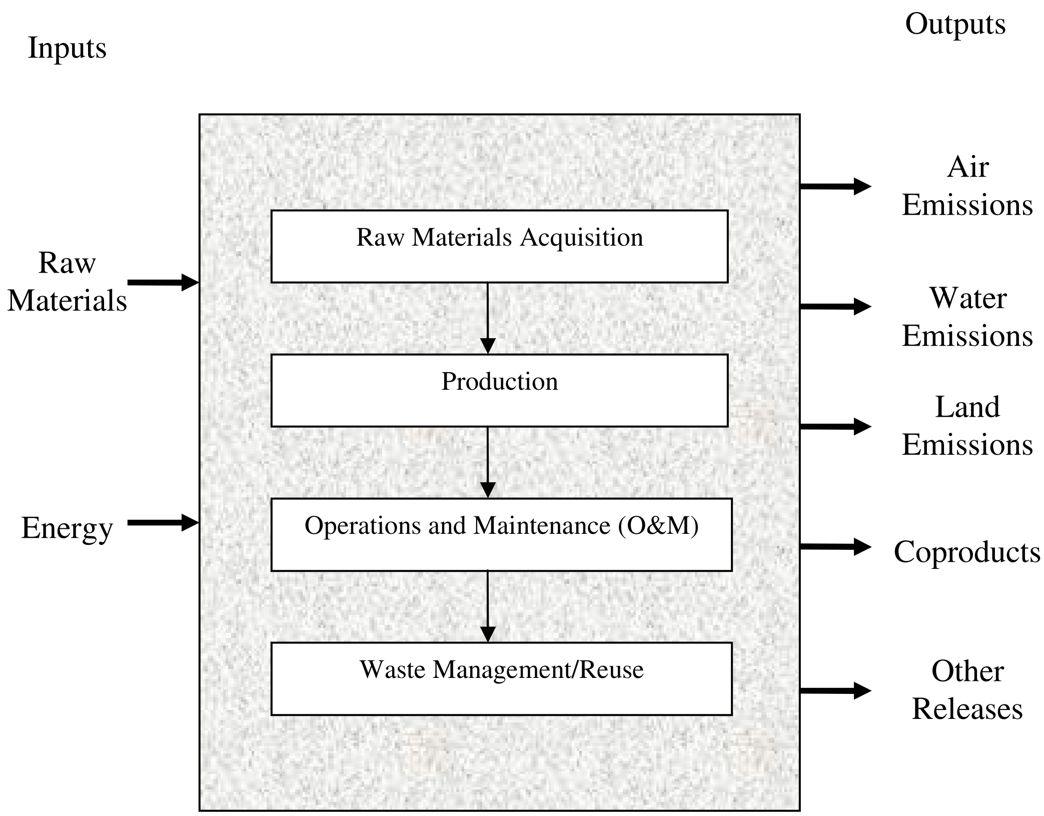

Figure 1. Stages of Life Cycle Analysis (U.S. Environmental Protection Agency and Science Applications International Corporation 2001)

Table 1. Summary of Advantages/Capabilities and Disadvantages/Limitations of existing processes for dealing with macronutrient, micronutrient, and pathogenic problems associated with CAFOs (AS = activated sludge)

Type of treatment process	Advantages/Capabilities	Disadvantages/Limitations
Anaerobic AS Treatment	Removes carbon Removes pathogens Produces biogas Small sludge production Technology well understood	Removes little nitrogen Removes little phosphorus Removes little metals
Anaerobic Biofilm Treatment	Removes carbon Removes pathogens Produces biogas Virtually no sludge production Technology well understood	Removes little nitrogen Removes little phosphorus Removes little metals
Aerobic AS Treatment	Remove carbon Oxidize nitrogen Technology well understood Large Process Volumes	Removes little phosphorus Electricity costs Removes little metals Large effluent nitrate Large sludge production Pathogens remain
Aerobic Biofilm Treatment	Remove carbon Oxidize nitrogen Technology well understood Less process volume than aerobic AS Less sludge production than aerobic AS	Removes little phosphorus Electricity costs Removes little metals Large effluent nitrate Pathogens remain
Anaerobic/Anoxic/Aerobic AS Treatment	Remove carbon Remove nitrogen Remove phosphorus Remove metals	Electricity costs Sludge production Pathogens remain
Mixed Anaerobic/Anoxic/Aerobic AS/Biofilm Treatment	Remove carbon Remove nitrogen Remove phosphorus Remove metals Less sludge, process volume than AS	Electricity costs Pathogens remain
Precipitation	Remove metals Remove phosphorus Technology well understood	Removes some carbon Removes little nitrogen Largest sludge production Removes little pathogens Cost of chemicals Impact of chemical production Sludge production and disposal Pathogens remain
Anammox Technology (Hellinga *et al.* 1998; van Dongen *et al.* 2001)	Remove nitrogen	Technology not well understood Subject to catastrophic upsets (Dapena-Mora *et al.* 2004) No carbon removed No metals removed No phosphorus removed Pathogens remain