MODELING AND OPTIMIZATION OF SYSTEMS FOR NUTRIENT RECOVERY FROM LIVESTOCK WASTE

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A mi familia, y a todos los que por mi vida pasaron.

No tenemos un tiempo escaso, sino que perdemos mucho.
La vida es lo bastante larga para realizar las mayores empresas,
pero si se desparrama en la ostentación y la dejadez,
donde no se gasta en nada bueno, cuando al final
nos acosa el inevitable trance final, nos damos cuenta
de que ha pasado una vida que no supimos que estaba pasando.

— Séneca, De la brevedad de la vida.

ACKNOWLEDGMENTS

Complete

ABSTRACT

To be completed.

RESUMEN

Completar.

PUBLICATIONS

This thesis is presented as a compendium of publications, where each of the chapters corresponds to a formal manuscript published in a scientific journal, or currently under review, and book chapters. The relation of manuscripts published or under review, and book chapters that comprise this dissertation is detailed below:

[1] E. Martín-Hernández, L.S. Guerras, and M. Martín. «Optimal technology selection for the biogas upgrading to biomethane.» In: *Journal of Cleaner Production* (2020), p. 122032.

[2] E. Martín-Hernández, Y. Hu, V.M. Zavala, M. Martín, and G.J. Ruiz-Mercado. «Analysis of incentive policies for phosphorus recovery at livestock facilities in the Great Lakes area.» In: *Resources, Conservation & Recycling* (Under Review).

[3] E. Martín-Hernández, M. Martín, and G.J. Ruiz-Mercado. «A geospatial environmental and techno-economic framework for sustainable phosphorus management at livestock facilities.» In: *Resources, Conservation & Recycling* (Under Review).

[4] E. Martín-Hernández, G.J. Ruiz-Mercado, and M. Martín. «Model-driven spatial evaluation of nutrient recovery from livestock leachate for struvite production.» In: *Journal of Environmental Management* 271 (2020), p. 110967.

[5] E. Martín-Hernández, A.M. Sampat, M. Martin, V.M. Zavala, and G.J. Ruiz-Mercado. «A Logistics Analysis for Advancing Carbon and Nutrient Recovery from Organic Waste.» In: *Advances in Carbon Management Technologies*. CRC Press, 2021, pp. 186–207.

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[7] M. Mohammadi, E. Martín Hernández, M. Martín, and I. Harjunkoski. «Modeling and Analysis of Organic Waste Management Systems in Centralized and Decentralized Supply Chains Using Generalized Disjunctive Programming.» In: *Industrial & Engineering Chemistry Research* 60.4 (2021), pp. 1719–1745.

CONTENTS

LIST OF FIGURES

ACRONYMS

1 INTRODUCTION

1.1 RATIONALE: OVERVIEW OF THE NUTRIENT PULLUTION CHALLENGE

Human population is experiencing a continous growth since end of the Black Death in the XIV century [1], which is at 7.8 billion as of 2020, and it is estimated to be at 9.7 billion and 10.9 billion by 2050 and 2100 respectively [7]. Population growth demands increasing amounts of food, which in turn requires an efficient food production system to support this growth. In this context, the development of different technical advacements has been a key factor to increase the productivity of the food production system. Notably, crucial developments were achieved in the late modern period[1], including the commercial production of phosphate in 1847 [5], the development of the Haber-Bosch process for the production of synthetic nitrogen-based fertilizers in 1913 [6], and the mechanization of agriculture and the development of the modern intensive farming in the XX century [3, 4].

Despite these advacemements have increased the productivity of agriculture and farming industries, multiple environmental impacts associated with them emerges, including water scarcity, greenhouse gases emissions, nutrient pollution of waterbodies, and soil degradation, among others. These threats must be carefully addressed in order to avoid the depletion of natural resources and reach a sustainable food production system.

Focusing on the impacts derived from agriculture and farming on the nutrient cycles, it can be observed that the natural cycles of phosphorus and nitrogen have been altered these activities [2]. Large amounts of nutrients are released into the environment in the form of synthetic fertilizers and livestock manure. Nitrogen and phosphorus are accumulated in soils, creating a nutrient legacy that is further transported to waterbodies by runoff. This process results in the eutrophication of waters, which can lead algal bloom episodes. Algal blooms are events resulting from the rapid increase of algae in a water system wich can be promoted by an excess of nutrients in water, altering the normal functioning of the aquatic ecosystem. Some algal blooms can releases toxins, and they cause hypoxia as a consecuence of the aerobic degradation of algall biomass by bacteria.

1 The terminology used in this dissertation for the periodization of human history follows the English-language historiographical approach. It should be noted that the late modern period is referred to as the contemporary period in the European historiographical approaches.

1.2 SCOPE AND OBJECTIVES OF THE THESIS

This thesis seeks to promote the recovery and recycling of nutrients contained in livestock waste by identifying the most appropiate technologies for phosphorus and nitrogen recovery at cattle and swine CAFOs, assessing the potential nutrient releases abatement that could be achieved by the deplyoment of these systems and analyzing incentive policies for their effective implementation at livestock facilities. Moreover, we introduce a systematic framework for evaluating, and selectiong the most suitable nutrient recovery system at CAFOs considering geospatial environmental vulnerability to nutrient pollution.

OBJECTIVE I: To perform a review of teh state-of-the-art of the processes for phosphorus and nitrgen recovery from livestock waste, identifying those processes whose implementation at CAFOs is feasible from a techno-economic perspective.

OBJECTIVE II: To identify environmental indicators for nutrient pollution, and use them to assess the potential for the abatement of phosphorus releases by deploying the processes previsously selected at livestock facilities at subbasin spatial resolution.

OBJECTIVE III: To develop a decision-support system for the evaluation and selection of nutrient recovery systems at livestock facilities integrating techno-economic data of the nutrient recovery technologies and environmental vulnerability to nutrient pollution information determined through a tailored geographic information system (GIS) in order to select the most suitable system for each particular livestock facility.

OBJECTIVE IV: To design and analyze potential incentive policies for the deployment of phosphorus recovery technologies at livestock facilities, as well as to study the fair allocation of limited monetary resources.

1.3 THESIS OUTLINE

This dissertation is strucutred in three parts. Part I is devoted to the study of phosphorus management and recovery, Part II studies the technologic options for nitrogen recovery, and Part III conduct a research for determining the best combination of units for biomethane production in order to integrate biogas production and nutrient recovery processes.

1.3.1 *Part I - Phosphorus management and recovery*

CHAPTER ?? - TECHNOLOGIES FOR PHOSPHORUS RECOVERY. This chapter performs a review of the main processes for phosporus recovery from livestock waste, identifyfing the most promising processes to be deployed at CAFOs using a mixed-integer nonlinear programming model.

CHAPTER ?? - ASSESSMENT OF PHOSPHORUS RECOVERY THROUGH STRUVITE PRECIPITATION. This chapter study the mitigation of phosphorus releases through the deployment of struvite precipitation systems in the watersheds of the contigous Unites States. Specific surrogate models to predict the production of struvite and calcium precipitates from cattle leachate were developed based on a detailed and robust thermodynamic model. In addition, the variability in the organic waste composition is captured through a probability framework based on Monte Carlo method.

CHAPTER ?? - GEOSPATIAL ENVIRONMENTAL AND TECHNO-ECONOMIC FRAMEWORK FOR SUSTAINABLE PHOSPHORUS MANAGEMENT AT LIVESTOCK FACILITIES. This chapter presents a decision support framework, COW2NUTRIENT (Cattle Organic Waste to NUTRIent and ENergy Technologies), for the assessment and selection of phosphorus recovery technologies at CAFOs based on environmental information on nutrient pollution and techno-economic criteria. This framework combines eutrophication risk data at subbasin level and the techno-economic assessment of six state-of-the-art phosphorus recovery processes in a multi-criteria decision analysis (MCDA) model. We aimed to provide a useful framework for the selection of the most suitable P recovery system for each aprticular CAFO, and for designing and evaluating effective GIS-based incentives and regulatory policies to control and mitigate nutrient pollution of waterbodies.

CHAPTER ?? - ANALYSIS OF INCENTIVE POLICIES FOR PHOSPHORUS RECOVERY. This chapter conduct a research on the design and analysis of incentive policies using the COW2NUTRIENT framewrok for the implementation of phosphorus recovery technologies at CAFOs minimizing the negative impact in the economic performance of CAFOs. Moreover, the fair allocation of monetary resources when the available budget is limited is studied using the Nash allocation scheme.

1.3.2 *Part II - Nitrogen management and recovery*

CHAPTER ?? - MULTI-SCALE TECHNO-ECONOMIC ASSESSMENT OF NITROGEN RECOVERY SYSTEMS FOR SWINE OPERATIONS. This

chapter performs a review of the main processes for nitrogen recovery at intensive swine operations. A multi-scale techno-economic analysis is performed to estimate the capital and operating costs for different treatment capacities, identifying the most promising processes.

1.3.3 *Part III - Nitrogen management and recovery*

CHAPTER **??** - OPTIMAL TECHNOLOGY SELECTION FOR THE BIOGAS UPGRADING TO BIOMETHANE. This chapter performs a systematic study of different biogas upgrading to biomethane processes in order to identify the optimal process attending to the particular characteristics of the biogas produced from livestock manure. Food waste and wastewater sludge are also included for comparison. We aimed to determine the optimal biomethane production processes for the potential combination of biomethane production and nutrient recovery processes into an integrated resources recovery facility.

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Part I

PHOSPHORUS MANAGEMENT AND RECOVERY

Complete introduction of Part I

Part II

NITROGEN MANAGEMENT AND RECOVERY

Part III

INTEGRATION OF ANAEROBIC DIGESTION AND NUTRIENT MANAGEMENT SYSTEMS

Part IV

APPENDIX