Decision making tool for industrial dairy sludge management: A real case study

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Introduction

Uruguay, a small country with a population of 3 million people, is the seventh largest exporter of dairy products in the world. Also, seventy percent of the milk produced in Uruguay is exported. Uruguay's commitment to sustainable practices can be reflected in the country brand "Uruguay Natural", which emphasize a genuine connection with nature. In this context, the dairy sector faces the challenge of properly managing its waste, from primary production to consumption, including industrial processes. An important type of high-organic-content waste generated is the sludge from the wastewater treatment systems of dairy processing plants, which produce liquid milk, powdered milk, and a significant range of mass- consumption products. Currently, the most common method of managing these sludges in Uruguay is their disposal in a landfill. However, this option is neither the most suitable for minimizing environmental impact nor the most cost-effective one. There are different alternatives for the disposal of these sludges, considering the sustainability of the entire value chain. Some of them include the distribution of digested sludges on dairy farms as soil amendment, composting, use as an energy source, or as a partial substitute for nutrients after drying and pelletization, among others. However, the environmentally proper management of these sludges often entails significant costs for companies, whose finances are strained by intense international competition.

How to select the most suitable path to minimize economic impact? This question resumes the aim of this work. It is addressed within the context of a case study involving an industrial plant located in the central region of the country. Limited attention has been devoted to the application of mathematical optimization tools specifically for the management of sludge within the dairy industry (Perimal et al. (2017), Yapiciočlu and Yeşilnacar (2021), Olajire and Shah (2009)). This research aims to develop a decision-making framework tailored for the board within the dairy industry, facilitating comparative analyses across diverse scenarios, that is, to solve a process synthesis problem (PSP) of sludge management within the framework of Process Systems Engineering (PSE). Different management alternatives were considered, with the selection criterion being the possibility of obtaining experimental data on efficiencies and costs at a real scale: combinations of chemical conditioning and mechanical dewatering, drying, on-field distribution as a soil amendment in dairy farms, use as fuel and disposal in sanitary landfills as a base case for comparison. The problem is implemented for a specific case, but by adjusting parameters related to geographic location, site-specific costs, and characteristics of the sludge to be disposed of, the tool is applicable to other cases.

Predicting the mechanical dewatering efficiency of a candidate technology is challenging, as this parameter depends on the type of sludge under consideration. This aspect is significant because the residual moisture content in sludge cakes impacts subsequent treatment costs due to increased volume. Thus, it is important to identify the primary variables within the dewatering process (Novak (2006), Richard I. Dick and Novak (1980), WAK (2006)). A second objective is to assess dewatering efficiencies for sludges of different origins, providing valuable information to extrapolate the results obtained in this case to other dairy plants.

Methods

a.- Building PSP tool. The problem consists of optimizing management cost per ton of sludge subject to a set of restrictions: 1.- mass and energy balances for each unit operation, 2.- operating requirements, 3.- environmental legal requirements and 4.- logic constraints. Combinations of technologies are analysed for the mechanical dewatering stage, drying at different final humidities, and final uses. Models for each operational unit are proposed, drawing on insights from prior research (Mangone et al. (2018), Porley Santana A. (2023)), real scale data and from literature (Mujumdar (2006)). Varying efficiencies in different unit operations, operational costs encompassing labor, energy, and other resources, as well as operational limitations are considered. For example, the suitability of a specific sludge for a particular drying process depends on meeting specific moisture conditions. Finally, the objective function aimed to minimize the daily operational costs linked with sludge management for the case study plant. The corresponding superstructure for the problem under study is illustrated in the figure 1. After collecting experimental data, to build the PSP it is necessary to generate the framework and translating it into a mathematical model. GAMS was chosen as the software for model implementation and optimization. The resulting problem is of the MILP type.

b.- Dewatering potential. Different types of sludge from dairy plants were analyzed: #1.- a physicochemical sludge from an ice-cream production facility, #2.- an aerobic digested sludge from a cheese manufacturing plant and #3.- a sludge from the anaerobic digester of a powdered milk processing plant (case study). In order to assess the effect of pressure on the dehydration of different sludges, as no commercial equipment was found for this purpose, an ad-hoc device was constructed. A detailed description will be presented in the extended version of the paper.

Results

a.- PSP model optimization. The findings unveiled that, the most cost-effective approach for a powdered milk production plant involves employing geotubes for dewatering, drying up to 85% solid content by utilizing boiler flue gas heating, and subsequently incinerating the dried sludge in the plant's boiler. Approximately 79% are attributed to costs associated with the mechanical dewatering process, 19% to the drying operation, and nearly 1% allocated to the required transportation. The cost of the optimal solution found is less than half of the cost of the current reference solution, which involves geotubes mechanical dewatering followed by disposal in a landfill. This underscores the economic significance of the mechanical dewatering stage and highlights the criticality of utilizing surplus heat as a source for the drying phase. Currently, sensitivity analyses are underway for other case studies, utilizing the experimental evidence as a foundational basis.

b.- Dewatering potential. All tested sludges behaved maintaining a constant moisture content (Maximum Dewatering Moisture) beyond a specific pressure threshold (Critical Dewatering Pressure). Despite this trend, each of the three samples showed distinct values for CDP and MDM. Results indicated that increasing the pressure beyond 7 bar did not further dewater the sludge in any of the cases. The maximum percentages of solids achieved for the different sludges were significantly different: 11%, 15%, and 19% for #2, #3, and #1, respectively.

Conclusion

A decision-making tool was developed for sludge management, integrating experimental data and information collected at a real scale plant as a case study. It is possible to generalize the tool by taking into account specific parameters, of which dehydration capacity is identified as a key factor, and a methodology for its evaluation is presented. Furthermore, an investigation into the inherent variability in dehydration among sludges of diverse origins will be presented, leading to the creation of an empirical method to determine dehydration efficiency under pressure.

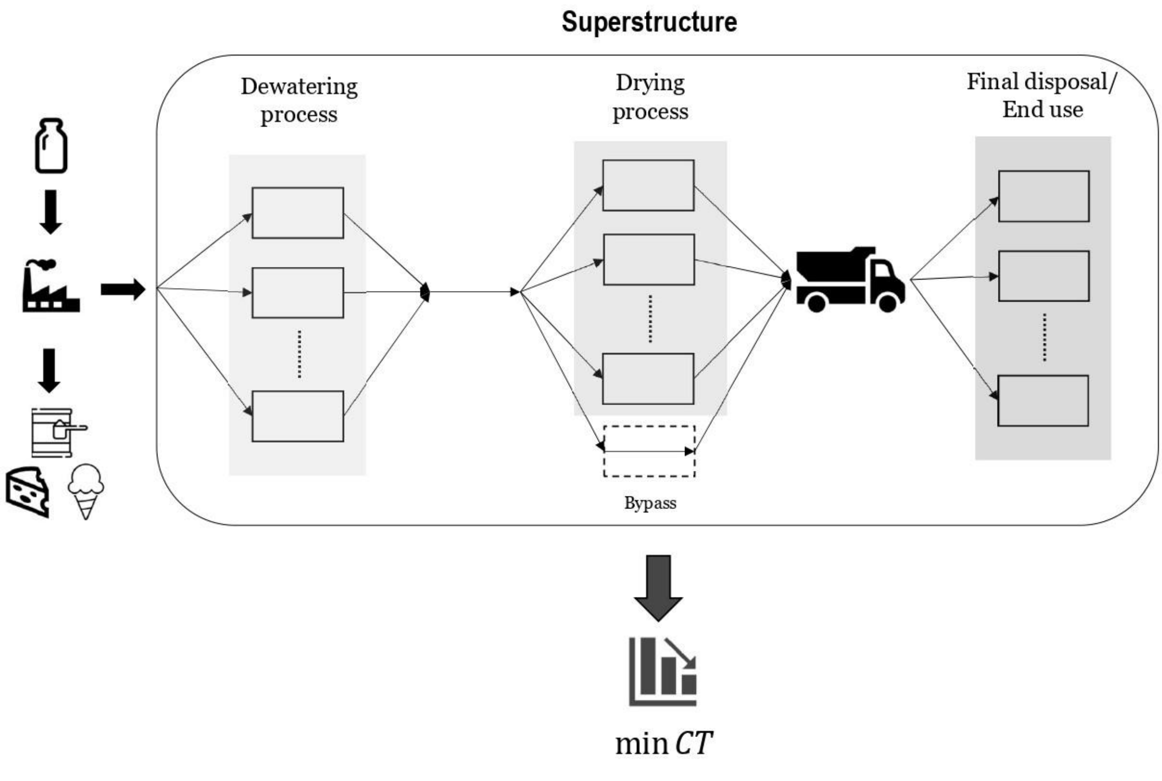

Figure 1. Schematic of the proposed superstructure

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