

Dewatering process: mathematical and experimental approach for optimal sludge management in dairy industry

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Abstract

The dairy industry is striving to reduce its environmental impact, with a particular focus on sustainable sludge management. A decision-making tool has been developed for Uruguayan dairy companies to optimize sludge management processes. This tool was created by proposing a superstructure and employing mathematical programming, allowing for a comprehensive evaluation of various operational alternatives. The tool evaluated various options, including dewatering, drying, and final disposal. The most cost-effective solution identified was the use of geotextile bags for dewatering, followed by drying and combustion. This alternative proved to be 20% cheaper than the baseline method and also provided a valorization alternative of the waste as a fuel. The tool's utility was demonstrated through sensitivity analyses.

To enhance the tool's accuracy, an experimental study was conducted to assess sludge dewaterability under pressure. Samples of sludge with varying origins and compositions were analyzed, revealing significant differences in the minimum moisture percentage achieved, despite similarities in the general shape of the curves. These findings enable a better selection of dewatering technologies based on the specific characteristics of each sludge, contributing to more efficient and sustainable management of dairy industry waste.

Keywords Process synthesis · Dewatering potential · Techno-economic evaluation · Optimization

Introduction

Uruguay, a small country with a population of 3 million people, is the ninth largest exporter of dairy products in the world. Seventy percent of the milk produced in Uruguay is exported and dairy products represent the fourth most important item of Uruguayan exports with an annual growth of 21 percent in 2022 [1]. The dairy sector, from primary production to consumption, including industrial production, faces the challenge of effectively managing its waste as part of sustainable production. This is in accordance with the policy of the Uruguayan state, which aims to preserve national resources and has implemented the country brand 'Uruguay Natural' emphasizing a genuine connection with nature. An important type of waste generated is the sludge from the

treatment systems of dairy product processing plants, which produce liquid milk, powdered milk, cheeses, yogurts, and a significant range of mass-consumption products. Managing these high-organic-content wastes in a way that generates minimal environmental impact is the challenge that local industries face.

Dairy wastewater in general has as characteristics: high biological oxygen demand (BOD) and chemical oxygen demand (COD) contents, high levels of dissolved or suspended solids including fats, oils, and grease, nutrients such as ammonia or minerals and phosphates [2–4]. The volume, concentration, and composition of the effluents are dependent on the type of product being processed, operating methods, and design of the processing plant [5]. For example, in a fluid milk packaging plant it is common to find effluents with low content of total suspended solids (0.09–0.45 g/l) and low chemical oxygen demand (0.95–2.4 g/l) [6], while in a cheese processing plant the effluent water usually has a high salt content (0.26–1.3 g/l) [5]. On the other hand processing butter or desserts generates an effluent which may contain a greater amount of sugars, fats, and suspended solids [2, 6]. As a result, over the years different methods of treating this

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effluent have been developed. The wastewater treatment generally consists of a series of physicochemical and biological treatments (aerobic or anaerobic). These treatments generate diverse types of sludge as waste with different properties and variable compositions.

There are several potential alternatives for the disposal of the sludge resulting from effluent treatment, some considering the sustainability of the entire value chain. One approach involves producing compost or vermicompost due to the high nutrient content, particularly phosphorus (P) and nitrogen (N) found in these sludges [7]. Similarly, its nutrient-rich composition makes it suitable for enhancing dairy farm's soil quality [8–10]. The potential to recover various valuable products through sludge management, including pigments, biochars, and biofuels was proposed [11, 12]. Alternatively, the sludge can be incinerated, serving as a fuel source. Lastly, authorized contractors can handle its removal for a fee. In Uruguay, it is commonly utilized as a soil amendment, and when this is not feasible, an external company is responsible for managing the sludge. The environmentally proper management of these sludges often entails significant costs for companies, whose finances are strained by intense international competition. In [13] the importance of geographical location in decision-making regarding dairy effluent treatments and the associated solid-liquid separation processes is highlighted. How to select the most suitable path to minimize economic impact in an environmentally friendly manner? In order to answer this question, our aim was to compare the alternatives with the possibility of obtaining energy from the sludge. It is addressed within the context of a case study involving an industrial plant located in the central region of the country.

Sludge separation is an important treatment stage, as it is pointed out by [14]. In that study, the authors propose employing natural coagulants to enhance dairy sludge separation. The residual moisture content in sludge cakes significantly impacts subsequent treatment costs, notably in transportation due to increased volume and drying processes. Thus, the selection and operational conditions of dewatering systems assume critical importance [15–17]. Dewatering efficiency depends on several physical, chemical and biological factors such as the ratio of fixed to volatile solids, the amount of fats and proteins, the content of trivalent cations and other agents used in sludge conditioning, and biological factors like the type of biological treatment from which they come: aerobic or anaerobic, the sludge residence time, and the presence of filamentous bacteria [18–20]. Conversely, the water content within sludge aggregates exhibits varying degrees of binding, ranging from loosely associated “free” water to tightly bound chemically linked water. These factors combined give rise to differences in sludge dewaterability. Several methods are proposed to evaluate dewaterability:

capillary suction time and filterability tests are two well-known methods [20]. The capillary suction time (CST) test is a valuable tool for comparing the dewaterability of sludge after different pretreatment methods. Similarly, the filterability test allows for the estimation of vacuum filtration capacity, enabling the comparison of conditioning agents or the dewatering ability of different sludges under vacuum conditions. However, these tests are not useful for predicting the dewatering efficiency of a specific sludge in equipment operating under pressure. For this purpose, it is advisable to conduct experiments at increasing pressures to evaluate the dewatering capacity.

Several alternatives to mechanical dewatering of sludge are available: rotary drum, vacuum filter, belt filter, decanter centrifuge, filter press, screw press, etc. [21–23]. In nearly all these cases, the prior incorporation of flocculants/coagulants is standard practice. Some rigorous models for dewatering processes have been developed [21–23]. Given its prevalence, sewage sludge has been extensively studied; however, the relationship between its mechanical dewatering efficiency and its chemical, physical, and biological characteristics remains incompletely understood [11, 19, 24]. Our research group has investigated this phenomenon by modeling dewatering systems, specifically geotextile and volute presses [25, 26].

Process synthesis tools have been employed in several studies to enhance the value of biomass waste [27–30]. However, limited attention has been given to applying mathematical optimization specifically for sludge management within the dairy industry [31–33]. This research develops a decision-making framework tailored for dairy industry boards, facilitating comparative analyses across diverse scenarios. For this purpose, we model and solve a *process synthesis problem* for sludge management within the framework of Process Systems Engineering (PSE). We also conduct sensitivity analysis to pinpoint critical parameters influencing the overall operational cost.

Effective process design relies on accurate efficiency and cost parameters for each unit operation. However, predicting the maximum achievable solids percentage for a specific sludge and technology remains challenging in sludge dewatering. Currently, no general empirical or phenomenological model exists for this purpose. To address this gap, our study focuses on three distinct sludges: a physicochemical sludge from a dessert processing plant (DPP), an anaerobic sludge from a cheese processing plant (CPP), and a sludge from the anaerobic digester of a powdered milk processing plant (PMPP). Each sludge is processed using its own dedicated dewatering technology at the dairy company. While experimental data is available for specific sludge-technology combinations, it cannot be reliably extrapolated to predict performance when applying the same technology to sludges with different properties. One way to estimate achievable

efficiency with a specific technology is to subject different sludges to the same test, thus enabling a comparison of their relative behavior.

Sludge management presents both an economic and environmental problem. To address this, this study aims to develop a mathematical model for sludge management to support decision-making within a dairy industry. To achieve this, experimental tests will be conducted to predict the mechanical dewatering of different sludge types and assess how pressure affects efficiency, thereby obtaining key parameters for model formulation. Additionally, sensitivity analyses will be performed to demonstrate the model's applicability and effectiveness.

Materials and methods

Dewatering potential

Dewatering test under pressure

A custom-built device was constructed. Methods such as the capillary suction time (CST) test allow for adequate comparison of different sludges in terms of their dewaterability. These tests are conducted under vacuum conditions, with a maximum pressure difference of 1 bar. However, dewatering methods that operate under positive pressure, such as screw presses, subject the sludge to higher pressure differences. Therefore, a pressure-based device provides a more accurate representation of the potential behavior of sludges in such systems. Our method enables the analysis of how varying applied pressures affect dewaterability, allowing us to infer whether an industrial device operating at higher pressures might achieve better performance with a given sludge. It consists of a steel cylinder with openings in the wall and an outer metal mesh. These openings allow for proper drainage of the water contained in the sludge when pressure is applied to it. A geotextile fabric bag (SoilTain® PP 105/105 DW, apparent pore opening 0.2 mm) with the same diameter as the steel cylinder is placed inside it. The bag is filled with 300 ml of sludge and sealed at the top with a plastic security seal. Subsequently, the cylinder is placed in the press. The pressure is carefully increased to the corresponding value

and held for the necessary time until no water drainage is observed (approximately 20–30 min). Tests were conducted by triplicate. After each test, the total solid content was determined by gravimetric method.

Samples of the flocculated sludge from each plant were received: physicochemical sludge obtained from an ice cream and dessert processing plant (DPP), anaerobic sludge from a cheese processing plant (CPP) and sludge from the anaerobic digester of a powdered milk processing plant (PMPP). The summary of the sludge characteristics can be seen in Table 1. Each unit utilizes a cationic polyelectrolyte as a flocculant, with dosages optimized experimentally at each plant. Total solids analyses were performed on these samples.

Dewatering performance in full scale units

The outlet moisture content of various operational dewatering units across the three indicated plants (DPP, CPP, and PMPP) was analyzed to establish a real-scale reference. A survey of samples was conducted at the outlet of the dewatering units. The sampling campaign took place between November and July. The analysis of outlet total solids was performed in triplicate for each sampling event, employing the same method as described in the previous section.

Process synthesis problem modelling

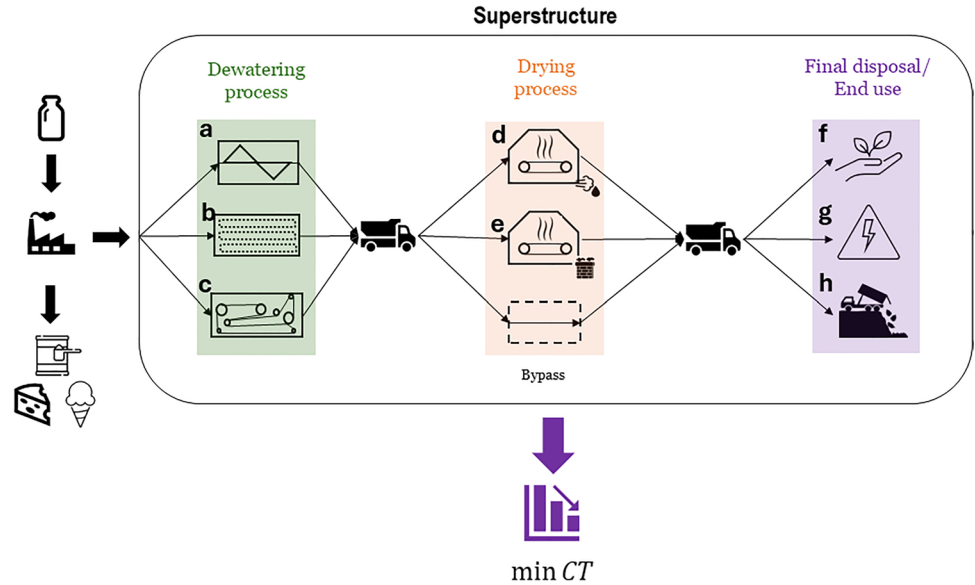
Study case definition

1. *Base case.* The tool relied on a case study of a milk processing plant for the production of powdered milk which generates 60 tons of wet sludge daily. The current sludge management process involves dewatering the sludge using a series of geotubes and then applied to land as a soil amendment.
2. *Alternatives considered.* In this work, sludge management alternatives will be explored involving one or more of the following stages in series: a dewatering stage, a drying stage, and various final destinations, with trans-

Table 1 Summary of the sludges to be processed, including their type and main characteristics

Plant	Sludge type	Sludge characteristics
DPP	Physicochemical sludge from a dessert processing plant	Lipid and protein-rich, undigested sludge
CPP	Anaerobic sludge from a cheese processing plant	Anaerobic pond digested sludge from activated sludge treatment, high salt content ($CL^{-} 1.5 g \times L^{-1}$)
PMPP	Anaerobic digester sludge from a powdered milk processing plant	Anaerobic digested from secondary sludge

Fig. 1 Schematic of the tool **a** screw press, **b** geotextile, **c** belt filter, **d** mobile bed dryer with through-flow (steam), **e** mobile bed dryer with through-flow (boiler flue gas), **f** soil amendment (boiler flue gas), **g** energy valorization as fuel, **h** landfill



portation stages between unit operations, as depicted in the superstructure presented in Fig. 1.

1. *Sludge dewatering.* Previous studies have explored the modeling and performance of various sludge dewatering technologies, being belt press, screw press, and geotubes [25, 26, 34]. Additionally, units of these types are currently in operation at various dairy plants. Therefore, these options will be considered in the model.
2. *Drying.* A crossflow bed dryer was pre-selected for the drying operation due to its superior efficiency compared to parallel flow dryers. Drum dryers were excluded from consideration due to the potential for sticking, given the specific characteristics of the sludge. The drying alternatives considered involve the utilization of two available energy sources and the final moisture content represents a decision variable of the problem. Showing the trade-off existed between the desired final moisture level and the energy cost required for drying. Two drying units were evaluated, one using flue gas from the plant's boiler as the heating fluid, and another using steam from the same boiler. It is important to note that the auxiliary costs are different for the two considered units. These costs were estimated based on the equipment catalogs and information provided by the company.
3. *Final disposal/end use.* The available final disposal possibilities for the company were analyzed utilizing the sludge as a soil amendment (the current practice) and land application. Additionally, the possibility of energy recovery by using the sludge as fuel in the

company's boiler is included. Technical limitations were identified through discussions with boiler technicians and reference to the equipment manual.

Framework development

The model aims to minimize the operational costs of sludge management while adhering to environmental restrictions for solids handling based on their final disposal. The focus is placed on operational costs as the company considers investment costs to be independently analyzed and easily integrated into the overall assessment. The proposed optimization model is subject to a set of constraints that include logical, technical, and operational limitations that ensure the feasibility and coherence of the generated alternatives. The specific mathematical expressions and details of the model are provided later in this section. The constraints referred to fall into one of the following categories:

1. Mass and energy balances for each unit operation. Models for each operational unit are proposed, and model parameters were obtained from prior research group experiences, real scale data provided by the dairy company and from literature [25, 26, 34].
2. Technical constraints. These reflect the physical and operational limitations of the equipment and processes involved, such as maximum or minimum flow rates, efficiency thresholds, or capacity limits. Varying efficiencies in different unit operations are considered [35].
3. Operational constraints. These include restrictions related to resource availability, such as heat sources, energy requirements, or transportation distances

4. Economic constrains. These involve operating cost for each unit operation and condition
5. Environmental legal requirements
6. Logical constraints. Two main logical constraints are considered: a. Unique Equipment per Unit Operation: For an alternative to be considered valid for evaluation, it cannot include two different pieces of equipment performing the same unit operation. For example, an alternative cannot include two different dryers or two different final disposal destinations. This ensures that each alternative represents a coherent and feasible process configuration, and b. Zero Flow through Unselected Unit Operations: The material flow through unit operations that are not selected in the evaluated process diagram is considered null. This means that if a unit operation is not part of the specific alternative being evaluated, it does not contribute to the material flow or cost calculations.

Finally, the objective function was defined. A mixed-integer nonlinear problem (MINLP) was formulated, drawing from pertinent literature [36–38] and the model was implemented in General Algebraic Modeling System (GAMS) software and solved using Solver SCIP (Solving constraint integer program algorithm).

General operation unit Figure 2 shows the schematic of the operation units. The basic model for a general operation unit adapted from bibliography [36–38] is shown in Fig. 2a. There are three types of material flows, principal material flows ($F_{p,k,c}$), added product to the operation ($R_{k,c}$) and the waste generated by the unit ($W_{k,c}$). The index p (in, out) indicates the position around the operation unit, the index k indicates the unit and the c indicates the component. The composition of the materials flows was simplified and only considered the water and the sludge as principal compounds.

The general component mass balance is defined in Eq. (1).

$$F_{in,k,c} + R_{k,c} = F_{out,k,c} + W_{k,c} \quad (1)$$

Mechanic dewatering process A typical dewatering process configuration is shown in Fig. 2b. It consists of a flocculation unit (a), a mixing tank where the flocculated sludge is generated (b) and the dewatering equipment (c).

In previous work, the techno-economic aspects and the mass balance for different equipment and different sludges were analyzed [34]. There are primarily two characteristics that define mechanical dewatering process (k_{DH}): the solid retention efficiency of the equipment (ϵ_{Retk}) and the solid content of the sludge ($X_{sol,k_{DH}}$) obtained at its outlet. With these parameters, the output streams of the operation can be defined.

$$F_{out,k,sludge} = \epsilon_{Retk} * F_{in,k,sludge} \quad (2)$$

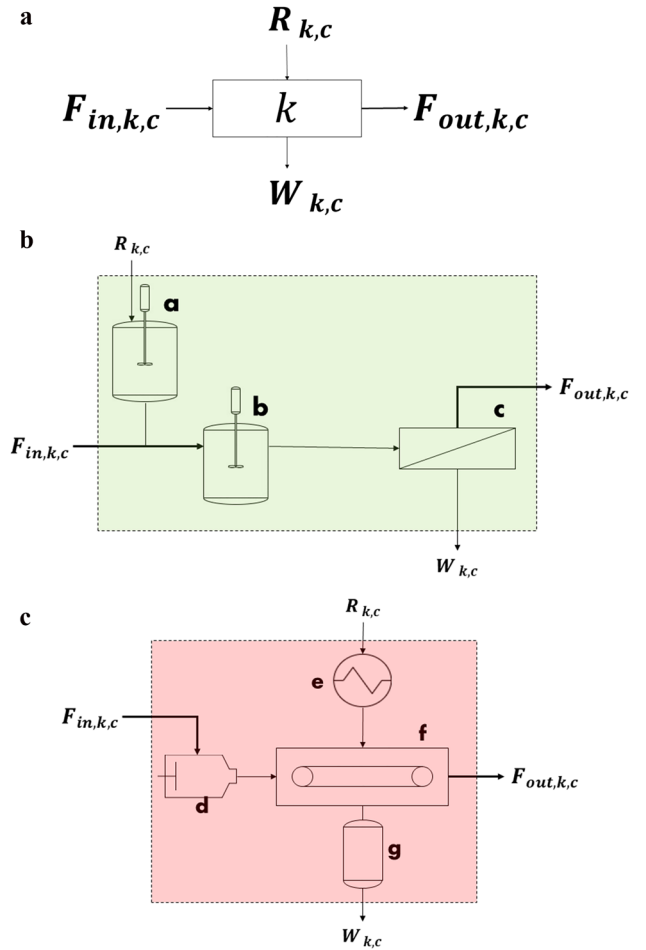


Fig. 2 Schematic of the unit operation **a** flocculation unit, **b** mixing tank, **c** dewatering equipment, **d** performing unit, **e** gas heater, **f** drying equipment, **g** gas treatment unit

$$F_{out,k_{DH},water} = \frac{F_{out,k_{DH},sludge} * (1 - X_{sol,k_{DH}})}{X_{sol,k_{DH}}} \quad (3)$$

Operational data from the selected equipment (geotextiles, screw press and belt filter) was collected at the company's dairy plants to obtain the required parameters. The experimental data and the tests conducted for this purpose are explained further below.

The amount of flocculant needed is proportional to the material flow entering the operation, translated to a mathematical form:

$$R_{k,c} = \delta_{k,c} * \sum_{cc} F_{in,k,cc} \quad (4)$$

$\delta_{k,c}$ is the relation between flocculant needed and the sludge produced. Normally the concentration of the flocculant solution is of the order of 0.05% w/w, so an assumed simplification is that all the material flow is composed of water.

Lastly, the operating cost can be estimated with a parameter and the total flow entering the operation.

$$\text{Cost}_{k_{DH}} = \$_{k_{DH}} * \sum_c F_{in,k_{DH},c} \quad (5)$$

where $\$_{k_{DH}}$ represents the operating cost of the dewatering equipment k_{DH} per ton of sludge in the feed, which includes the cost of electricity, labor, maintenance, and flocculant.

Drying process The typical drying equipment configuration is presented in Fig. 2c, including the preforming of the sludge (d), the gas heater (e), the drying equipment itself (f) where transfer is occurring, and the gas treatment unit (g) needed for the content of ammonia in the sludge which could finish in the gas phase and has an environmental impact. Analogously to the previous section, the drying operation is modeled using the solid retention parameter and the solid content in the outlet stream.

$$F_{out,k,sludge} = \epsilon_{Ret,k} * F_{in,k,sludge} \quad (6)$$

$$F_{out,k_{Dry},water} = \frac{F_{out,k_{Dry},sludge} * (1 - X_{sol,k_{Dry}})}{X_{sol,k_{Dry}}} \quad (7)$$

where $X_{sol,k_{Dry}}$ is the solid content of the outlet stream of the drier (k_{Dry}). We aim to optimize the overall process cost by allowing the model to select the most cost-effective solids percentage. Therefore, variable $X_{sol,k_{Dry}}$ is treated as a decision variable within the optimization framework. Neglecting sensible heat, the heat required for drying ($Q_{k_{Dry}}$) is calculated as in Eq. (8) where λ_0 is the enthalpy of water evaporation.

$$Q_{k_{Dry}} = \lambda_0 * W_{k_{Dry},water} \quad (8)$$

The operating cost must be determined. The drying cost consists of two costs: the calorific energy cost associated with the evaporation of the water content in the solid and the cost of auxiliary equipment.

The first is taken as the cost of the heat source ($\$_{Energy,k_{Dry}}$) multiplied by the calculated heat and divided by an exchange efficiency of the equipment ($\epsilon_{Energy,k_{Dry}}$). The information that is generally available from drying equipment suppliers presents the auxiliary cost in terms of the evaporative capacity of the dryer, therefore, the auxiliary cost is estimated based on the mass flow of evaporated water. The auxiliary cost

includes the operating cost of auxiliary services such as gas treatment, electricity cost for preforming of solids and the movement of solids and gases.

$$\text{Cost}_{k_{Dry}} = \frac{Q_{k_{Dry}} * \$_{Energy,k_{Dry}}}{\epsilon_{Energy,k_{Dry}}} + \$_{Add,k_{Dry}} * W_{k_{Dry},water} \quad (9)$$

$\$_{Add,k_{Dry}}$ is the cost per ton of evaporated water associated with the aforementioned auxiliary processes.

Final disposal/end use Final disposal not only determines the final cost but also the environmental impact. In order to model this section, the cost associated with three alternatives final destinations ($\text{Cost}_{k_{FD}}$) are considered: soil amendment, landfill, or sludge valorization as fuel. The total cost of utilizing sludge as fertilizer encompasses transportation, land application, and mandatory environmental analyses. It can be directly estimated based on the total quantity of sludge requiring disposal. The cost of treatment conducted by an external company (landfill) can be estimated in the same way. Consequently, the costs will be estimated by calculating the cost per ton of sludge ($\$_{FD,k_{FD}}$) to be disposed of and multiplying it by the total quantity of sludge requiring disposal ($\sum_c F_{in,k_{FD},c}$). Finally, the cost associated with its use as boiler fuel includes two parts, on the one hand the cost of managing the ash formed which is estimated as a fraction of the burned sludge multiplied by a parameter (similar to the previous costs) and on the other hand, there is the “savings” associated with the use of this as fuel, which is estimated from how much the burning of the sludge contributes in heat ($F_{in,k_{FD},sludge} * LHV_{sludge}$) compared to the needed to evaporate the residual moisture in the sludge ($F_{in,k_{FD},water} * \lambda_0$). In Eq. 10, the disposal cost is mathematically described.

$$\text{Cost}_{k_{FD}} = \$_{FD,k_{FD}} * \sum_c F_{in,k_{FD},c} \alpha_{c,k} + \frac{F_{in,k_{FD},water} * \lambda_0 - F_{in,k_{FD},sludge} * LHV_{sludge}}{LHV_{fuel}} * \$_{fuel} * y_{boiler} \quad (10)$$

$\alpha_{c,k}$ is a parameter which indicates the component has a contribution or not to the cost, this parameter is important in the cost associated with the boiler because only the sludge generate ashes ($\alpha_{water,boiler} = 0$, $\alpha_{sludge,boiler} = 0, 55$), on the other cases is going to be 1. LHV_c is the lower calorific value of the component c, $\$_{fuel}$ is the fuel price and, y_{boiler} is the binary variable which indicates the boiler selection. The binary variable y_k models the decision of whether or not that process was selected, a value of one indicates that the process k was selected.

Transport Transportation cost is estimated by considering the distances between processes ($d_{k,kk}$), the cost of transportation per kilometer traveled ($\$_{trans}$), and the capacity of the transportation medium (Cap_{trans}) and the total amount transported ($\sum_c F_{in,kk,c}$).

$$Cost_{trans} = \sum_k \sum_{kk} \sum_c \frac{F_{in,kk,c} * \$_{trans} * d_{k,kk} * y_k}{Cap_{trans}} \quad (11)$$

Restrictions To ensure that the solution to the problem has physical meaning, basic constraints are established.

Maximum humidity allowed for drying Firstly, for the sludge to be effectively dried in this type of dryer, it is required that it be in a solid state; therefore, it must have a maximum allowable moisture content ($X_{max,kDry}$).

$$\frac{F_{in,kDry,water}}{F_{in,kDry,water} + F_{in,kDry,sludge}} \leq X_{max,kDry} \quad (12)$$

Critical humidity The maximum humidity achievable through the drying process ($X_{critical}$), at which the system reaches equilibrium with the air used to dry the material of interest, is a value that must be determined through experimental testing. This value cannot be established theoretically and requires practical trials to obtain accurate results.

$$\sum_{kDry} \frac{F_{in,kDry,water}}{F_{in,kDry,water} + F_{in,kDry,sludge}} * y_{kDry} \leq X_{critical} \quad (13)$$

Boiler restrictions On the other hand, the company's wood-burning boiler allows the burning of sludge as an alternative fuel. Even so, it must meet the following specifications: the maximal moisture allowed ($X_{max,boiler}$), and the minimal lower heating value needed ($LHV_{min,boiler}$). The dilution of the sludge was considered using the mass fuel flow of the boiler (m_{boiler}).

$$\frac{F_{in,boiler,water} + (m_{boiler} - F_{in,boiler,water} - F_{in,boiler,sludge}) * X_{fuel}}{m_{boiler}} \leq X_{max,boiler} \quad (14)$$

$$\frac{F_{in,boiler,sludge} * LHV_{sludge} + (m_{boiler} - F_{in,boiler,water} - F_{in,boiler,sludge}) * LHV_{fuel}}{m_{boiler}} \leq LHV_{min,boiler} \quad (15)$$

Zero-flow enforcement for no selected processes Once the physical meaning has been assured, it is necessary to postulate restrictions that allow the selection of alternatives in the model and the union equations of the system. In order to tell

the model that it should select between alternatives, we use the binary variables combined with the big M criterion [38].

$$F_{in,k,c} < M * y_k \quad (16)$$

$$F_{out,k,c} < M * y_k \quad (17)$$

where M is a huge quantity (10^6).

Single unit selection per process In addition, the system must indicate that a maximum of one unit operation will be chosen per process; this means that there will not be multiple dryers or multiple final destinations. Moreover, it is imperative to select the final destination.

$$\sum_{kDH} y_{kDH} \leq 1 \quad (18)$$

$$\sum_{kDry} y_{kDry} \leq 1 \quad (19)$$

$$\sum_{kFD} y_{kFD} = 1 \quad (20)$$

Connecting flows equations It is necessary to have equations that indicate the connection between the stages. This can be expressed in mathematical language as follows.

$$F_{0,c} = \sum_{kDH} F_{in,kDH,c} \quad (21)$$

$$\sum_{kDH} F_{out,kDH,c} = \sum_{kDry} F_{in,kDry,c} \quad (22)$$

$$\sum_{kDry} F_{out,kDry,c} = \sum_{kFD} F_{in,kFD,c} \quad (23)$$

Nonzero final disposal flow Lastly, the model needs to select a disposal pathway, which means:

$$\sum_{k_{FD}} F_{in,k_{FD},c} \geq m * y_{k_{FD}} \quad (24)$$

m has a value of 10^{-6} .

Objective function In this case, the idea is to reduce the total operating cost ($Cost_{Total}$), therefore, the objective is to select the process with the minimum operating cost.

$$Cost_{Total} \quad (25)$$

And the total cost can be determined as the sum of each operation selected.

Table 2 Model's parameters

Name	Description	Value	Unit	Source
$F_{0,c}$	Initial mass flow of the component c	Sludge: 1.2 Water: 58.8	ton/day	Plant data
$\epsilon_{Ret,k}$	Solid retention efficiency of the process k	Screw press: 0.77 Geotextile: 0.91 Belt filter: 0.91 Dryers: 0.99 Final disposal: 1	ton/ton	Estimated from plant data
$X_{sol,k_{DH}}$	Solid content of the out of dewatering process k_{DH}	Screw press: 0.15 Geotextile: 0.14 Belt filter: 0.14	ton/ton	Estimated from experimental and plant data
$\delta_{k,c}$	Flocculant to input sludge ratio	Dewatering processes: Water: 0.8 Sludge: 0	ton/ton	Plant data
$\$_{k_{DH}}$	Single cost of dewatering process k_{DH}	Screw press: 5.4 Geotextile: 4.9 Belt filter: 5.9	USD/ton	Estimated from company data
$\$_{Energy,k_{Dry}}$	Calorific energy cost of the drying process k_{Dry}	Steam: $2.3 \cdot 10^{-5}$ Boiler flue gas: 0	USD/KJ	Estimated from Aspen Plus database
$\$_{FD,k_{FD}}$	Cost of disposal per ton of solid to treat	Soil amendment: 23 Boiler: 5 Landfill: 32	USD/ton	Company data
$d_{k,kk}$	Distance between k and kk	$k_{DH} \rightarrow k_{Dry} : 1$ $k_{Dry} \rightarrow k_{FD} : 20$ $k_{Dry} \rightarrow k_{Boiler} : 1$	Km	Company data
α_c	Component contribution to the disposal cost	Boiler: water 0, sludge 0.55 Others: 1	–	Plant data
λ_0	Enthalpy of water vaporization	2257	KJ/ton	Bibliography
$\epsilon_{Energy,k_{Dry}}$	Calorific energy efficiency of the drying process k_{Dry}	0.6	–	Estimated based on expert judgment
$\$_{Add,k_{Dry}}$	Auxiliary cost per ton of evaporated water	10	USD/ton _{water}	Estimated based on catalogs and expert judgment
LHV_{sludge}	Lower calorific value of dried sludge	6216	KJ/Kg	Estimated based on elemental analysis
LHV_{fuel}	Lower calorific value of boiler's fuel	11,070	KJ/Kg	Plant data
$\$_{fuel}$	Cost per ton of boiler's fuel (wood)	92	USD/ton	Company data
$\$_{trans}$	Cost per Km of transport	11.8	USD/Km	Company data
Cap_{trans}	Transport capacity	20	Ton	Company data
$X_{max,k_{Dry}}$	Maximum humidity allowed for drying	0.9	ton/ton	Experimental
$X_{critical}$	Critical moisture	0.92	ton/ton	Experimental
X_{fuel}	Moisture of the fuel	0.35	ton/ton	Plant data
m_{boiler}	Capacity of the boiler	200	ton/day	Plant data
$X_{max,boiler}$	Maximal moisture allowed in the boiler	0.5	ton/ton	Plant data
$LHV_{min,boiler}$	Minimal lower calorific value needed in the boiler	6270	KJ/Kg	Plant data

$$\begin{aligned} \text{Cost}_{\text{Total}} = & \sum_{k_{DH}} \text{Cost}_{k_{DH}} * y_{k_{DH}} + \sum_{k_{Dry}} \text{Cost}_{k_{Dry}} * y_{k_{Dry}} \\ & + \sum_{k_{FD}} \text{Cost}_{k_{FD}} * y_{k_{FD}} + \text{Cost}_{\text{trans}} \end{aligned} \quad (26)$$

Parameters The parameters required by the model are detailed in Table 2. Several parameters were determined experimentally through physicochemical analysis of the sludge (Experimental). Other parameters are specific to the problem at hand and were obtained directly from the company (Plant and company data). Parameters such as outlet percentage of solids of the dewatering equipment were

Table 3 List of symbols and definitions

Name	Type	Description	Unit
c	Set	Component (water, sludge)	–
p		Port (in, out)	–
k		Process (screw press, geotextile, belt filter, mobile bed dryer with through-flow (steam), mobile bed dryer with through-flow (boiler flue gas) soil amendment, energy valorization as fuel, landfill)	–
k_{DH}		Dewatering process (screw press, geotextile, belt filter)	–
k_{Dry}		Drying process (mobile bed dryer with through-flow (steam), mobile bed dryer with through-flow (boiler flue gas))	–
k_{FD}	Set	Final disposal (soil amendment, energy valorization as fuel, landfill)	–
$F_{0,c}$	Parameter	Initial mass flow of the component c	ton/day
$\epsilon_{\text{Ret},k}$		Solid retention efficiency of the process k	ton/day
$X_{\text{sol},k_{DH}}$		Solid content of the out of dewatering process k_{DH}	ton/ton
$\delta_{k,c}$		Relation between flocculant and sludge produced	ton/ton
$\$_{k_{DH}}$		Single cost of dewatering process k_{DH}	USD/ton
λ_0		Enthalpy of water vaporization	KJ/ton
$\$_{\text{Energy},k_{Dry}}$		Calorific energy cost of the drying process k_{Dry}	USD/KJ
$\epsilon_{\text{Energy},k_{Dry}}$		Calorific energy efficiency of the drying process k_{Dry}	–
$\$_{\text{Add},k_{Dry}}$		Auxiliary cost per ton of evaporated water	USD/ton
$\$_{\text{FD},k_{FD}}$		Cost of disposal per ton of solid to treat	USD/ton
α_c		Component contribution to the disposal cost	–
LHV_{sludge}		Lower calorific value of dried sludge	KJ/Kg
LHV_{fuel}		Lower calorific value of boiler's fuel	KJ/Kg
$\$_{\text{fuel}}$		Cost per ton of boiler's fuel	USD/ton
$\$_{\text{trans}}$		Cost per Km of transport	USD/Km
$d_{k,kk}$		Distance between k and kk	Km
$\text{Cap}_{\text{trans}}$		Transport capacity	Ton
$X_{\text{max},k_{Dry}}$		Maximum humidity allowed for drying	ton/ton
X_{critical}		Critical moisture	ton/ton
X_{fuel}		Moisture of the fuel	ton/ton
m_{boiler}		Capacity of the boiler	ton/day
$X_{\text{max,boiler}}$		Maximal moisture allowed in the boiler	ton/ton
$LHV_{\text{min,boiler}}$		Minimal lower calorific value needed in the boiler	KJ/Kg
$F_{p,k,c}$	Positive variable	Component c stream in the port p of the process k	ton/day
$R_{k,c}$		Added mass flow of component c in the process k	ton/day
$W_{k,c}$		Waste generated by process k	ton/day
$Q_{k_{Dry}}$		Heat exchanged in drying process k_{Dry}	KJ/day
$X_{k_{Dry}}$		Solid content at the outlet of k_{Dry}	ton/ton
$\text{Cost}_{k_{DH}}$		Cost of the process k_{DH}	USD/day
$\text{Cost}_{k_{Dry}}$		Cost of the process k_{Dry}	USD/day
$\text{Cost}_{k_{FD}}$	Variable	Cost of the final destiny k_{FD}	USD/day
$\text{Cost}_{\text{trans}}$	Positive variable	Transport cost	USD/day
$\text{Cost}_{\text{Total}}$	Positive variable	Total cost	USD/day

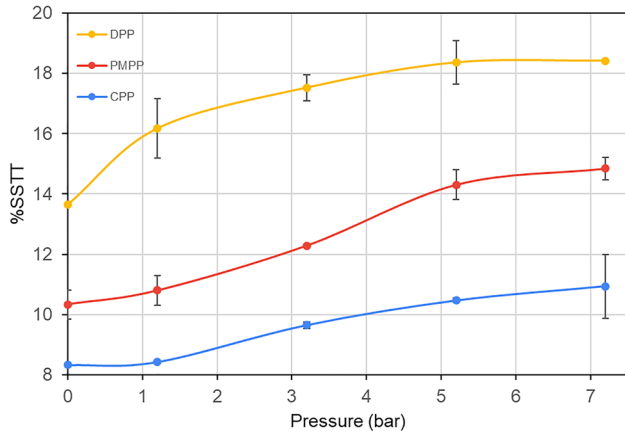


Fig. 3 Average solid content with its standard deviation for samples of different sludge types after applying the corresponding pressure using the ad-hoc equipment

estimated based on measurements from the company's real equipment (Company data) and extrapolated with experimental data (Experimental data) obtained with the device created to measure dewaterability. Additionally, some parameters were estimated from data obtained through communication with the company and that originated from prior techno-economic studies (Estimated from company data). Finally, some parameters were extracted or estimated from relevant literature.

Model implementation The sets, parameters, and variables of the de MINLP problem are summarized in Table 3. Local sensitivity analysis was performed by varying the parameters of interest while keeping the rest of the problem's parameters fixed.

Results and discussion

Dewatering potential

Dewatering test under pressure results

In Fig. 3, the results of the variation in the total solids content in each sludge with respect to the applied pressure can be observed. The test proved to be suitable in its operation and demonstrated good reproducibility of results, showing low dispersion in the replicates.

DPP sludges reached a solids percentage of over 18% under low pressure, which was maintained for pressure values greater than 3 bar. On the other hand, the PMPP and CPP sludges continued to dehydrate as the applied pressure increased, reaching lower solids values: 15% for PMPP and 11.5% for CPP. Results indicated that increasing the pressure beyond 7 bar did not further dewater the sludge in any of the

Table 4 Outlet total solids of full-scale dewatering units

Plant	Dewatering process	Total solids at the outlet	# samples
DPP	Screw press	16 ± 3%	9
CPP	Belt filter	11 ± 1%	3
PMPP	Geotextile tubes	14 ± 1%	6

cases. The test allowed for the comparison of the performance of different sludges in different equipment. For example, the equipment available in the DPP plant was a screw press, which dehydrated the sludge to an approximate solids content of 18%. Therefore, it could be said that this press has the capacity to bring the sludge to a pressure greater than 5 bar. This indicated that none of the other tested sludges were expected to have such dewaterability in a screw press. This distinction underscores the importance of considering both the inherent characteristics of the sludge and the performance of the dewatering equipment when designing and optimizing wastewater sludge management processes.

Dewatering performance in full scale units

Table 4 summarizes the experimental results of the full-scale dewatering unit trials. Due to their operating principles, belt filters and screw presses dewater sludge by applying pressure. Geotextile tubes also subject the sludge to pressure, with the maximum pressure corresponding to the height of the sludge column it supports. Dewatering mechanisms are varied and not solely attributable to pressure, particularly in the latter case. The dewatering process in geotextile tubes occurs over several months as the tube is filled and allowed to drain until it reaches its solid capacity. Despite these arguments, the results obtained from the industrial-scale equipment align with those obtained in laboratory tests, as the percentage of solids follows the same order: DPP sludge exhibits the highest degree of dewatering, followed by PMPP and lastly CPP. This experimental information allowed for the evaluation of the relative behaviors of the sludges and was useful for predicting the achievable solids percentage for a given sludge in different equipment. For instance, if considering the implementation of a screw press at the CPP plant, it was not expected that this equipment would achieve dewatering efficiencies exceeding 11–12%, as was the case with the undigested sludge from the DPP plant. Based on the real scale results, the achievable solids percentage for PMPP sludge ($X_{sol,k_{DH}}$, see Table 2) was determined to be 14% for geotextile tubes. The achievable solids percentage in the screw press and belt filter was estimated at 15% based on the pressure presumably attainable in this equipment.

Process synthesis problem- model optimization— study case

The final problem formulation resulted in a mixed-integer nonlinear programming (MINLP) problem due to the presence of a nonlinear term. This nonlinearity arises from defining the dryer outlet moisture content as a decision variable, which makes the outlet sludge mass flow rate dependent on this continuous variable. The model comprises 125 equations and 92 variables.

The findings revealed that the most cost-effective approach for a powdered milk production plant involved employing geotubes for dewatering, drying up to 92% solid content by utilizing boiler flue gas heating (critical moisture), and subsequently incinerating the dried sludge in the plant's boiler. Approximately 79% were 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 was less than 80% of the cost of the current management practice, which involves geotubes mechanical dewatering followed by land application as a soil amendment. 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. The best five optimal alternatives are presented in Table 5, with a fixed output moisture content of 92% total solids (critical moisture). In all cases, a significant improvement was observed over the current situation, emphasizing the imperative to employ boiler flue gas for sludge drying to reduce both transportation and energy costs.

Furthermore, valorization was the preferred approach among the three best management options; secondly utilizing the sludge as a soil amendment and the disposal in landfill is too expensive to be considered an option. The presentation of data in this manner enables the decision-maker to conduct a thorough evaluation of the viability of each alternative for implementation.

Switching from flue gas to steam for sludge drying resulted in a 93% increase in cost compared with the base case (Fig. 4). In this scenario, the most cost-effective option was to use a screw press for dewatering, which achieves a

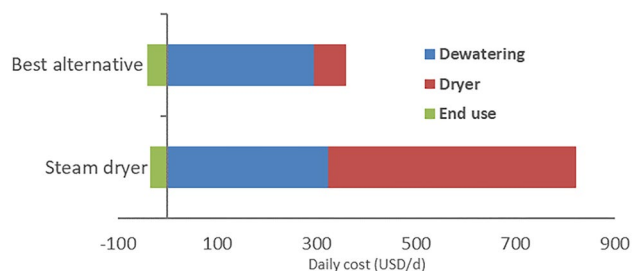


Fig. 4 Cost comparison between optimal alternative and steam dryer (the negative value in End Use indicates fuel savings due to sludge combustion)

higher level of dehydration. As a result, the expected drying cost in this case was 63% of the total cost, highlighting the significant economic impact of this process.

The most economically favorable alternative must also undergo an analysis related to the process's sustainability. In the identified optimal solution, the sludge is dried and subsequently incinerated in the boiler, leading to energy consumption and CO₂ emissions. However, the drying process utilizes waste heat from the boiler exhaust gases, which would otherwise be released into the atmosphere. Furthermore, the heat generated from burning the sludge offsets the need to burn an equivalent amount of biomass that would have been used to meet the plant's energy requirements, which would similarly have generated CO₂.

Applicability of the Model to Other Facilities. This study focused on a specific Uruguayan dairy plant, which limits its direct generalizability. Nevertheless, the underlying methodology and the decision-making tool are highly transferable. The analytical framework, rooted in dewatering experiments, mathematical modeling, and cost estimation, can be adapted to other dairy industries or even broader manufacturing contexts. While the specific parameters and data inputs would require recalibration to reflect distinct operational conditions, the tool's decision support capability remains broadly applicable at a country level. Key adaptability constraints include significant variations in dewatering potential, the accuracy and structure of cost estimations, and the availability of reliable operational data in new settings. While

Table 5 Best five optimal alternatives

Ranking	Management alternative	Relative total cost
Optimal solution	Geotextile—Boiler flue gas dryer—Boiler	0.79
1	Screw press—Boiler flue gas dryer—Boiler	0.84
2	Belt filter—Boiler flue gas dryer—Boiler	0.93
3	Geotextile—Boiler flue gas dryer—Soil amendment	0.94
4	Screw press—Boiler flue gas dryer—Soil amendment	0.97
5	Geotextile—Boiler flue gas dryer—landfill	1.02

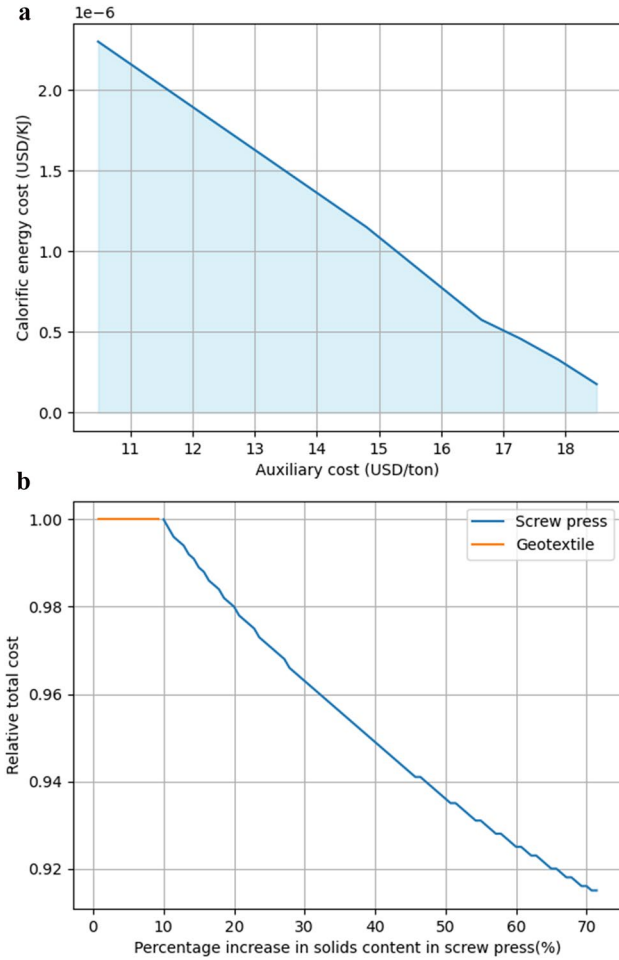


Fig. 5 Sensitivity analysis results

full-scale validation across all sludge types and technologies remains a crucial step for future work, the consistent behavior observed between laboratory-scale and industrial-scale dehydration of similar sludges lends confidence to the model's underlying assumptions and its practical applicability.

Sensitivity analysis—study case

Two distinct sensitivity analyses were undertaken (Fig. 5). One examined the impact of drying on global costs, while the other focused on the impact of dewatering equipment.

As it is shown in the previous section, the impact of the drying process on associated costs necessitated an investigation into the influence of drying parameters on alternative selection. An initial study was carried out to determine the impact of specific parameters of the drying process on the total management alternative cost. From an economic standpoint, drying cost is primarily affected by energy cost ($\$_{Energy, k_{Dry}}$) and auxiliary expenses ($\$_{Add, k_{Dry}}$). Therefore, the

variation of the total cost with the variation of these parameters was evaluated. The analysis revealed a relationship between these values. Figure 5a compares the auxiliary drying costs and heating costs for different drying technologies or processes. The shaded area represented the zone where drying costs are more economically viable compared to direct wet sludge incineration in the boiler. For example, if the cost of thermal energy is 1 USD/KJ, an auxiliary cost of up to 15 USD/ton is admissible for operations such as solids and gas transportation, sludge pre-forming, and gas treatment. If sludge drying remained desirable for further cost reduction in management, the focus should be on selecting drying equipment with both the initial equipment cost and the heat source cost falling within the blue zone of the graph (Fig. 5a).

Secondly, it was interesting to evaluate whether the dewaterability of the sludge affects the choice of dewatering equipment. It is known that presses can increase their pressure to values much higher than those obtained using geotubes. One could seek to answer how much the difference in solids content should be between these operations and geotubes. For this analysis, the case study was proposed without altering the destination or considering a drying stage in order to study only the impact of the dewatering step.

In Fig. 5b, one can observe how the relative cost varies with the increase in the dewaterability of the presses compared to the geotubes. The solids content at the outlet of the press system ($X_{sol, press system}$) is calculated using Eq. 27.

$$X_{sol, press system} = \left(1 + \frac{\%Inc, press system}{100} \right) * X_{sol, geotextile} \quad (27)$$

$\%Inc, press system$ is the solid content increase at the outlet of the press system, which is a relative measure of efficiency between the press system and the geotextile. In other words, a 15% increase means that if the geotextile has the capacity to obtain a sludge with 10% solids, the press with the same sludge would obtain 11.5% solids content. The results demonstrated that for values greater than 10%, it was more economically viable to use a screw press instead of geotubes. To achieve this analysis, the percentage increase in concentration at the outlet of both presses varied up to 70% relative to the solids content of the geotubes. The model never selected the filter press over the geotubes or the screw filter; it is presumed that this is due to the low solid retention efficiency of the equipment.

Conclusion

A decision-making tool has been developed for the dairy industry, enabling the selection of optimal sludge management alternatives by considering specific parameters such as

distances, transportation costs, and dewatering and drying efficiencies. Complementing this, an experimental setup was implemented to evaluate sludge dewatering capacity under pressure, allowing us to infer dewatering efficiency in industrial equipment by comparing the behavior of the studied sludge with that of industrial sludges processed in candidate systems. These advancements provide a foundation for optimizing sludge management in the dairy industry and offer potential for broader applications. While a full-scale validation across all sludge types and technologies remains a crucial step for future work, the consistent behavior observed between laboratory-scale and industrial-scale dehydration of similar sludges provides confidence in the model's underlying assumptions and its practical applicability. The tool represents a first step toward a more general solution for sludge management in diverse contexts. Future work should focus on expanding experimental databases on sludge properties and separation efficiencies, as well as exploring additional management alternatives to enhance its applicability.

Author contributions Agustín Porley: conceptualization, formal analysis, investigation, methodology, software development, visualization, and writing—original draft. Jonathan Lacuesta: experiment performance, data interpretation. Soledad Gutiérrez: conceptualization, methodology, writing—review and editing, supervision, resources, and funding acquisition.

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Declarations

Conflict of interest The authors declare that there are no competing interests.

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