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Research article

Do investments in phosphorus recovery from dairy processing wastewater pay off?

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ABSTRACT

While phosphorus fertilizers contribute to food security, part of the introduced phosphorus dissipates into water bodies leading to eutrophication. At the same time, conventional mineral phosphorus sources are increasingly scarce. Therefore, closing phosphorus cycles reduces pollution while decreasing trade dependence and increasing food security. A major part of the phosphorus loss occurs during food processing. In this article, we combine a systematic literature review with investment and efficiency analysis to investigate the financial feasibility of recovering phosphorus from dairy processing wastewater. This wastewater is particularly rich in phosphorus, but while recovery technologies are readily available, they are rarely adopted. We calculate the Net Present Value (NPV) of investing in phosphorus recycling technology for a representative European dairy processing company producing 100,000 tonnes of milk per year. We develop sensitivity scenarios and adjust the parameters accordingly. Applying struvite precipitation, the NPV can be positive in two scenarios. First, if the phosphorus price is high (1.51 million EUR) or second if phosphorus recovery is a substitute for mandatory waste disposal (1.48 million EUR). However, for a variety of methodological specifications, the NPV is negative, mainly because of high input costs for chemicals and energy. These trade-offs between off-setting pollution and reducing energy consumption imply, that policy makers and investors should consider the energy source for phosphorus recovery carefully.

1. Introduction

Phosphorus fertilizers have contributed to an increase in agricultural yields over the last century. However, a large proportion of the phosphorus dissipates into water bodies causing environmental damage like eutrophication (Scholz and Wellmer, 2013; Tonini et al., 2019). Moreover, the global mineral phosphorus supply is finite, and the scarcity and regional concentration of phosphorus cause of supply risks in the food value chain (Schroder et al., 2011). As food processing and production waste, for example from dairy processing, lead to major losses, recovering phosphorus from waste could both reduce pollution and enhance food security (Cordell and White, 2014; Chowdhury et al., 2017; Weikard and Seyhan, 2009).

Dairy processing produces phosphorus-rich wastewater. Conventionally the wastewater is treated, resulting in a sludge and dischargeable water. However, the application of this sludge to agricultural soils is inefficient, causes phosphorus run-off and is increasingly regulated (Ashekuzzaman et al., 2019). Another option is to produce secondary fertilizers from sludge. This mitigates potential negative pollution impacts from sludge application while closing material flow loops (Shi et al., 2021). However, despite advanced development efforts, adoption of such phosphorus recovery technologies is rare. The European Commission (2020b) has initiated an assessment of the current wastewater directive, the wastewater directive governs member state law dealing with the use and disposal of sludge. The reform aims to establish EU market access for recycled fertilizer to facilitate a more sustainable phosphorus cycle.

The objective of this paper is to assess the economic feasibility of investments in phosphorus recovery processes from the perspective of a dairy processing firm. We review the literature to identify process specifications that allow the recycling of phosphorus from dairy processing wastewater. Based on this information, we estimate Net Present Values (NPVs) of phosphorus recovery operations, which are scaled for average sized dairy processing companies in Europe. We transform the NPV model to calculate the levelized cost of phosphorus to analyze the break-even price for recycled phosphorus. Next, we estimate the technical efficiency of the process specifications to identify best practices

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Acronyms

Acronym	*Definition*
NPV	Net Present Value
HTC	Hydrothermal Carbonization
IRR	Internal Rate of Return
LCOP	Levelized Cost of Phosphorus
DEA	Data Envelopment Analysis

and determine the sensitivity of the results. The findings will inform adoption decisions, by clarifying in which scenarios the investment of phosphorus recycling in dairy processing is profitable.

We extend the literature in the following dimensions. First, most research is focused on either environmental indicators or technical advancements (Tonini et al., 2019) and literature on profitability of phosphorus recovery applications is relatively sparse. Among the few studies making an economic analysis are Molinos-Senante et al. (2011) who conducted a cost benefit calculation and explicitly included the prevention of environmental damages. Daneshgar et al. (2019) analyzed the costs of chemicals needed to determine the optimal specification of the phosphorus recovery process. However, both studies consider the case of municipal wastewater treatment which differs largely from dairy wastewater in both volume and composition (Molinos-Senante et al., 2012; Daneshgar et al., 2019). We focus on dairy wastewater because it has a higher organic matter and phosphorus content, while a lower heavy metal contamination compared to municipal wastewater (Shi et al., 2021), making the investigation of phosphorus recovery from this waste source an interesting business proposition. Second, unlike municipal phosphorus recycling plants, dairy processors treat the wastewater on-site and are privately owned, implying a more profit-oriented investment decision making context. Therefore, our research contributes to the literature by providing decision support for policy makers, investors, and dairy processors that aim to foster private investment in phosphorus recycling.

In the remainder of this paper, we describe how we conducted a systematic literature review to identify references that simultaneously deal with phosphorus recycling and dairy processing wastewater. We subsequently extract process data to construct process specifications. We use these specifications to calculate NPVs in order to evaluate the profitability of technologies described in the literature. Finally, we calculate technical efficiency scores of the different phosphorus recovery specifications to determine best practices. We find most technical literature sources do not provide enough information to construct process specifications. We also find that phosphorus recovery from dairy processing is not profitable with the base scenario but can be profitable under high phosphorus prices and when including revenues from saving disposal costs.

2. Background

Wastewater that accrues during dairy processing must be treated before it can be discharged into the environment. Conventionally, wastewater treatment in the dairy industry merely consists of separating water that can be discharged from a sludge containing solid matter. The sludge is rich in phosphorus and can be used directly as a fertilizer (Shi et al., 2021). Yet due to of the presence of toxic contaminants, the European Union increasingly restricts sludge applications (Hu et al., 2021). Alternatively, thermal or chemical extraction as well as decontamination can be used to recover secondary fertilizers from the sludge (Fig. 1). Such secondary fertilizers have similar fertilizing properties to rock phosphorus, the main source of mineral phosphorus fertilizer (Huygens et al., 2019). They are also easier to store and transport compared to sludge. There are several ways to recover phosphorus and this technology is still under development (Shi et al., 2022). Here we focus on the most advanced and most widely applied in literature.

2.1. The phosphorus recovery process

Large dairy processors treat their wastewater on-site, yielding sludge as the waste product. As the treatment steps may vary (Shi et al., 2021), we consider conventional approaches described in the literature.[1] One option, sludge drying, still leads to environmental problems, because the dried sludge can be toxic, even for plants (Croffie et al., 2022). Another viable pathway to deal with wastewater sludge is incineration. Incinerators are designed to deal with sludge quantities that are a magnitude larger than those produced by even the largest dairy processors in the EU. The sludge would have to be transported to a central incinerator plant, which we assume as too costly. For these reasons we consider it unlikely for dairy processors to implement either sludge drying or incineration.

A third approach involves hydrothermal carbonization (HTC) and the precipitation of Struvite salts, which can be combined or operated on their own. With hydrothermal carbonization the sludge is heated under pressure for 2 h to yield hydrochar and a phosphorus-rich liquor. The hydrochar can be used either as a fertilizer, a brown coal replacement in energy production or a soil improver (Hu et al., 2021).

Struvite precipitation occurs in a reactor, directly from sludge or from the liquor resulting from hydrothermal carbonization. Struvite is a phosphorus salt (its chemical name magnesium ammonium phosphate hexahydrate) and is formed in solutions which are saturated with magnesium, ammonium and phosphate ions. The inputs to produce Struvite from the wastewater are shown in Fig. 2. If the liquor contains heavy metals, they have to first be removed using oxalic acid, which decreases the solubility of the metals. Once precipitated, the heavy metals can be removed. Next, magnesium-chloride and sodium-hydroxide are added, which leads to the formation of phosphorus salts (Struvite) in the solution. In a final step, the Struvite is separated from the effluent (Numviyimana et al., 2020, 2022).

2.2. Adoption of phosphorus recovery technology

The European Union (EU) has made the recovery of biologically derived fertilizers a priority (European Commission, 2020b), to ensure an increase in circularity and a decrease in resource use in general. Circularity here refers to the reintroduction of waste streams, replacing the use of raw materials. The EU has pledged to reduce nutrient losses by 50 % while keeping soil fertility constant. Nutrient recycling is part of the strategy to reach this goal. All member states must implement regulations and incentives to achieve said goals (European Commission, 2020a). Currently, producers of recycled fertilizer have to seek permission to sell it from each national regulator. Changes in regulations will allow trade of recycled phosphorus within the common market of the EU (European Commission, 2019a). The application of sludge is already regulated and limited by EU regulations (European Commission, 2019b). Meanwhile, in the absence of recovery mandates, dairy processing firms need to decide to invest in additional recovery

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[1] The dairy processing wastewater treatment begins with air flotation to remove fats, oil and grease. Lime is added to control the pH of the water. In the following step, aerobic bacteria digest the organic components. Lactic acid bacteria ferment lactose to produce lactic acid, which in turn precipitates milk proteins. Additionally, phosphorus is concentrated by adding metal salts in the form of aluminium- and iron-sulphates and iron-chlorides. The insoluble precipitate is recovered by separating it from the water. Depending on the remaining pollution and local discharge limits, the separated water can already be discharged or must be treated again. The recovered precipitate is collected as sludge, from which phosphorus could be recovered (Ashekuzzaman et al., 2019).

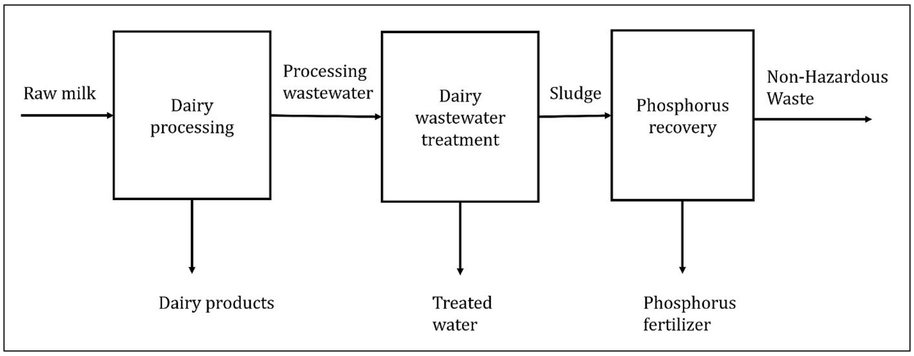

Fig. 1. Schematic overview of phosphorus recovery. The figure is a simplified exposition from Shi et al. (2021).

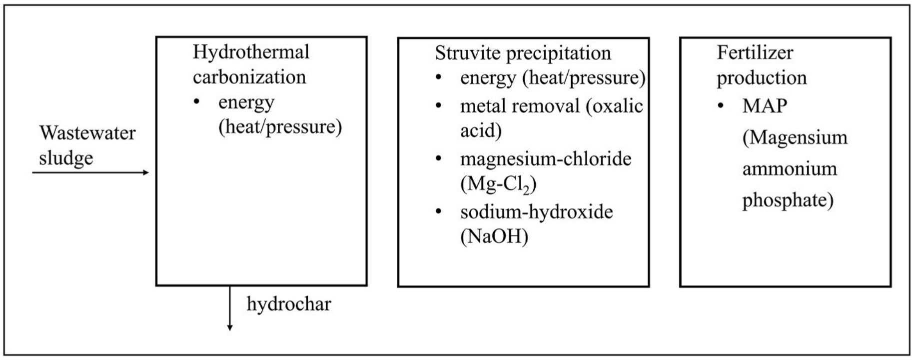

Fig. 2. Steps and inputs of phosphorus recycling.

technologies. Mandatory recovery would be much easier to implement but bears the risk of further increasing concentration in the dairy processing industry (Gardebroek et al., 2010; Koppenberg and Hirsch, 2021).

From a firm's perspective, the adoption of phosphorus recovery technology should be profitable. Implementation requires an initial investment, followed by costs and revenues derived from the recovery itself. We here assess the profitability of phosphorus recycling of a dairy processing firm. We assume that all cash flow changes stemming from the investment are reflected in the model and are independent from the other cash flows of the firm. Thus, a NPV larger than zero would mean that implementing recycling is more profitable than not. As processing firms could save substantial disposal costs, we include these savings as additional revenue in the sensitivity analysis (Medina-Martos et al., 2020).

3. Methods & data

To evaluate the profitability of investments in phosphorus recovery technology, the research consists of two consecutive steps (Fig. 3). First, we systematically analyzed the literature for cost and revenue data the of and from the recovery process. This allowed us to gather and extrapolate information from all published phosphorus recovery experiments focusing on dairy production. In a second step, we calculated the profitability of each of these specifications using the Net Present Value approach. Then we determined the production efficiency of the different recovery processes to determine the most efficient processes. In a final step, we computed the sensitivity of the investment profitability of the efficient process specification to the changes in key variables such as processing quantity, sludge content, discount rate, disposal costs, phosphorus prices and energy prices.

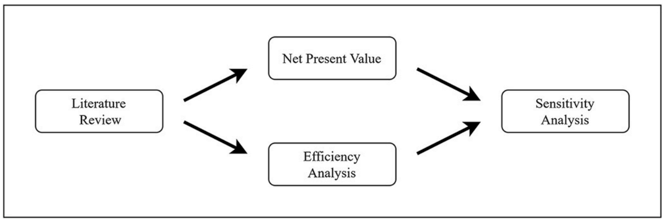

Fig. 3. Flowchart of the individual research steps.

3.1. Systematic literature review/model parametrization and assumptions

To assess the economic feasibility of phosphorus recovery we aim to review the state of the current literature regarding information that is relevant to the investment in phosphorus recovery in dairy processing wastewater. We conducted a systematic review according to PRISMA guidelines (Page et al., 2021). We searched Scopus for peer-reviewed English language articles using the following search strings reflecting a combination of phosphorus removal and the effluent source dairy processing: TITLE-ABS-KEY ("phosph* recovery") OR TITLE-ABS-KEY ("struvite recovery") OR TITLE-ABS-KEY ("phosph* extraction") AND TITLE-ABS-KEY ("dairy") OR TITLE-ABS-KEY ("milk") OR TITLE-ABS-KEY ("cheese") OR TITLE-ABS-KEY ("whey"). After the initial screening and selection, we supplemented the located sources with a backward citation analysis.

We only included research that dealt with the extraction of phosphorus from dairy procession waste. We excluded several sources dealing with dairy cattle manure, phosphorus chemistry that were not aimed at nutrient recovery and fertilizer applications. We included all literature review papers. After the screening, the remaining 97 articles were thoroughly analyzed to extract recovery applications and their experimental specifications. Details of the selection process are described in section 1 of the Appendix.

We extracted inputs and outputs from the phosphorus recovery experiments to construct material balances for every process specification.

The material balance includes energy and chemicals as inputs and phosphorus as output. Most articles did not report input quantities but initial molar concentrations, i.e. target concentration ratios and pH values, which we used to compute input quantities. To estimate the quantity of acid and base needed, we had to assume the absence of buffer compounds as the true quantities were not recorded in the literature. We suggest that future research on recycling processes, should more thoroughly inform about buffer compounds and material balance quantities. Moreover, we calculated the energy inputs for a range of hydrothermal carbonization temperatures. An example for the determination of the material balance quantities and a visualization of the data can be found in the Appendix.

We complemented the process specifications from the systematic literature review with further info related to upscaling the experimental processes. These include for instance expenditures for Struvite precipitators and hydrothermal carbonization at scale, production quantities of a representative dairy processor, and others (see Table 1 for an overview of these additional variables with corresponding literature sources).

Finally, we extracted prices of electricity (EUROSTAT, 2023a), natural gas (EUROSTAT, 2023b) and phosphate from EUROSTAT (2023e). The phosphorus price is calculated for the price of pure phosphorus from the price of triple superphosphate in Germany. Chemical prices and machine investments were adjusted for inflation with sector-specific price indexes (EUROSTAT, 2023d).

3.2. Net Present Value calculation

The calculation of NPV as a profitability indicator comprised several steps (Molinos-Senante et al., 2011; Yanore et al., 2023). First, for each process identified in the systematic literature review, we identified an initial investment I and cash flows R_t in each period t after the initial investment has been made arising from the sales of Phosphorus fertilizers. We discounted the value of these future cash flows into the starting year using discount rate *i* to make them comparable. A simplistic decision rule would be that firms should invest in all projects with a positive NPV. The discrete NPV can thus be formulated as follows:

$$NPV(i,n) = -I + \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{1}$$

where *n* is the number of considered periods, i.e. the lifespan of the technology. As an alternative profitability measure, we set the NPV equal to zero to determine the internal rate of return (IRR) of the investment:

$$\mathrm{NPV}(i) = -\mathrm{I} + \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} = 0 \tag{2}$$

This implies feasibility of the investment, if the discount rate the investor requires for the investment is below the IRR. In this case, the difference between the discount rate and the IRR generates the positive value of the investment. If an investor must choose between several alternatives, the IRR serves as a measure of profitability that can be compared across investment options (i.e., different technologies). The cash flow is calculated with the following equation.

$$R_t = p_t * q_t - w_t * x_t \tag{3}$$

Where p_t and q_t are vectors of the product price and production quantity at time t, respectively. The costs are the product of a vector of input prices w_t and quantities x_t.

The cash flows of the investment can be divided into three different parts, namely the investment, the recurring costs and the revenues. In the model the investment depended on the type of technology used to recover phosphorus, while the recurring costs depended on the quantity of sludge that is processed.

The price in the analysis was based on existing data, yet we were interested in long-term impact of the investment. Therefore, we divided discounted prices by discounted quantities to calculate the levelized cost of phosphorus in order to analyze how prices affect the profitability (Aldersey-Williams and Rubert, 2019; Borenstein, 2012). The levelized cost LOCP is defined by the price necessary to equalize the discounted production quantity with the discounted production costs C_t.

$$\begin{aligned} \sum_{t=1}^{n} q_t \frac{LCOP}{(1+r)^t} &= \sum_{n=0}^{n} \frac{C_t(q_1,\ldots,q_n)}{(1+r)^t} \Leftrightarrow \\ LCOP &= \frac{\sum_{t=0}^{n} \frac{C_t(q_1,\ldots,q_n)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{q_t}{(1+r)^t}} \end{aligned} \tag{4}$$

The production cost begins in $t = 0$ and thus includes the capital costs. An intuitive explanation of the LCOP is the discounted production cost divided by discounted output quantity. The levelized cost is the real price of phosphorus necessary to make the investment profitable.

3.3. Technical efficiency analysis

The estimation of the profitability in the previous subsection allows a comparison of the process specifications. However, the ranking relies on the input and output prices which are hard to predict. Efficiency mea-

Table 1
Parameters in NPV calculation.

Description	Source	Value	unit
Investment expenditure for Precipitation	Egle et al. (2015)	252,000	EUR
Investment expenditure for Hydrothermal Carbonization	Medina-Martos et al. (2020)	785,971	EUR
Discount rate		3	%
Duration of investment		15	y
Produced milk		100,000	t/y
Sludge in kg per t of processed milk (ranging between 0.2 and 18)	European Commission. Joint Research Centre (2019)	10	kg/t
Phosphorus content in g per sludge in kg	Khalaf et al. (2022)	57	g/kg
Disposal costs per t of sludge (ranging between 160 and 330)	Medina-Martos et al. (2020)	245	EUR/t
Price per kg of pure phosphorus from triple-superphosphate	*EUROSTAT (2023a)*	0.22	EUR/kg
−10th percentile price	*EUROSTAT (2023e)*	0.17	EUR/kg
−90th percentile price	*EUROSTAT (2023e)*	0.27	EUR/kg
Gas price	*EUROSTAT (2023b)*	0.05	EUR/kWh
−90th percentile price	*EUROSTAT (2023b)*	0.04	EUR/kWh
Electricity price	*EUROSTAT (2023a)*	0.16	EUR/kWh
−90th percentile price	*EUROSTAT (2023a)*	0.11	EUR/kWh

Note: The parameters without a reference are based on the authors expertise.

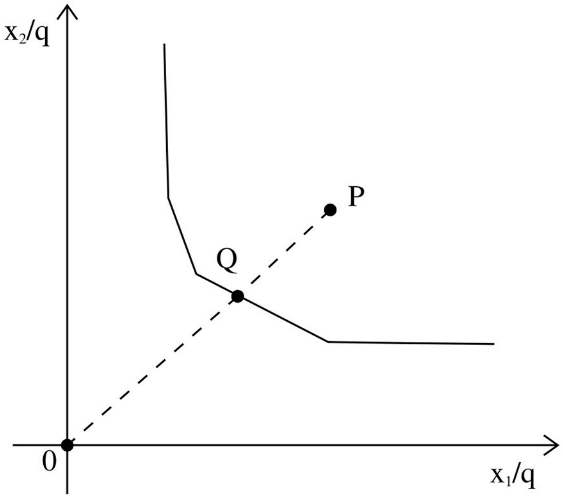

Fig. 4. Input-oriented technical efficiency calculated with DEA for two inputs x_1 and x_2 and one output q.

surement can determine best practices from a technical point of view within a particular sample (Oude Lansink and Reinhard, 2004; Rebolledo-Leiva et al., 2022). Inefficient process specifications use more inputs to produce a given quantity of outputs than the efficient ones. The profitability estimation on the other hand could mask inefficient practices since prices may provide an advantage in a particular year. Technical efficiency was estimated using the input quantities used and output quantities produced in each recovery specification. Using Data Envelopment Analysis (DEA) we identified process specifications that were producing on the frontier, meaning they produced the same amount of output with the least possible input (Coelli et al., 2005). Fig. 4 shows the measurement of technical efficiency in a two-input space with one output. P is the process specification under consideration and Q represents a process specification on the piece-wise isoquant. The technical efficiency TE is the ratio of the distance from the origin with Q over the distance from the origin to P.:

$$TE = 0Q/0P \tag{5}$$

We employed an input-orientated DEA model using the input and output data that were computed based on the literature review. The analyzed process specifications were differentiated by input use, for example some technologies relied heavily on heat energy while others used chemical inputs. We ran the following linear programing model to calculate technical efficiency scores θ for each firm:

$$\begin{aligned} \min_{\theta,\lambda} \quad & \theta \\ \text{s.t.} \quad & -\mathbf{q}_i + \mathbf{Q}\lambda \geq \mathbf{0} \\ & \theta \mathbf{x}_i - \mathbf{X}\lambda \geq \mathbf{0} \\ & \lambda \geq \mathbf{0} \end{aligned} \tag{6}$$

The literature review featured many different inputs complicating the efficiency analysis. We created data corresponding to one year of phosphorus recycling. To construct the dataset, we used the material balance that were the basis of the NPV calculation in the previous section. We aggregated the production inputs $\mathbf{x}_i$ where i refers to the three categories capital, energy and chemicals. First, we calculated the expenditure for each input $\mathbf{x}_i$:

$$e_i = \sum x_i * w_i \tag{7}$$

For capital, we made the simplifying assumption, that the entire capital input has the same performance over the entire lifetime of the project and that there would be a linear depreciation with no remaining value at the end of a 15-year period. The yearly capital expenditure was calculated as follows with μ as yearly capital expenditure, x as total capital and $(r+d)$ discount rate plus depreciation rate as per unit cost of capital. This makes the production constant, allowing us to estimate the efficiency scores in a cross-sectional sample. The calculation of the capital expenditure was:

$$\mu = \sum x \cdot (r + d) \tag{8}$$

The inputs were aggregated using market prices by weight, by summing the product of price and quantity with the unit input in EUR. The price w for the aggregated inputs was 1 except the capital index which has cost of capital as corresponding price.

3.4. Sensitivity analysis

We used the most efficient set of technologies, defined as process specifications with production on the technical efficiency frontier, to estimate profitability of recycling. Some of the sources indicated a range for the parameters of interest. Others did not indicate these parameters conclusively. To check whether the results generalize over a variety of contexts, we calculate the sensitivity of the result to a reasonable range of key parameters (Tonini et al., 2019). Some of the variability will be known when making the investment decision. Other variables may change only after the decision has been taken and the investment has been implemented. We identified several scenarios that decision makers are likely to face (Table 2). The scenarios are illustrated below.

The capacity of the Struvite precipitator and hydrothermal carbonization unit that we considered is mainly designed for municipal wastewater treatment plants. Since the volume of wastewater is considerably larger in these plants compared to the amount of wastewater that accrues in dairy processing plants, we tested the sensitivity of the profitability of the recovery technology between large and extra-large sized dairy processors. We expected that, due to the more efficient capacity use and economies of scale, the investment would be particularly profitable for large dairy operations.

Another important source of variation is the amount of sludge per kg milk that can be used to recover phosphorus. In the main process specification, we assumed the average of the reported sludge occurrence ratios in milk production (Table 1). In addition, we tested the sensitivity of the profitability to changes in the sludge to milk ratio, which can result from the production of different dairy products.

The discount rate of the investment will ultimately depend on a risk-free interest rate determined by the general economic conditions and the risk characterized by the variation in the returns. We initially chose a low value. In the sensitivity analysis, we doubled the rate to see how this would affect the profitability.

A major argument for implementing phosphorus recovery is the environmental harm posed by current practices. Currently, sludge spreading on agricultural land is still possible in many EU member states. However, if this practice was to be banned, processing firms would have to pay for waste disposal. To estimate how savings in

Table 2
Overview of scenarios.

n	Name	Description
1	larger processor	double the size of dairy processor and thus sludge quantity
2	higher sludge content	increase sludge occurrence in from 10 to 18 kg per tonne of processed milk
3	higher discount rate	increase discount rate from 3 to 6 %
4	disposal savings	reduction of disposal costs adds 245 EUR/t of sludge to revenue
5	high phosphorus prices	90th percentile price
6	low phosphorus prices	10th percentile price
7	high energy price	90th percentile price
8	crisis scenario	(high energy + phosphorus price) combination of 5 & 7

disposal costs would affect the profitability of phosphorus recovery technology (Medina-Martos et al., 2020) we added a revenue of 245 EUR per tonne of processed sludge in one sensitivity scenario (Table 1).

Phosphorus and energy prices varied greatly in the last years. Price increases for the output will increase profitability while price increase for the inputs will lower it. In addition, we considered that the recovered phosphorus can be a direct substitute for commercially traded fertilizers. We assumed 2022 prices in the initial estimation. To include possible variation, we deflated a time series of energy and phosphorus prices with a consumer price index (EUROSTAT, 2023c, 2023d) to the 2022 price level and used the 90th and 10th percentile as an estimate for a high or low-price environment.

4. Results

After reviewing the abstracts of the search results, the systematic literature search yielded in total 97 articles, from which we could extract 77 different phosphorus recovery process specifications in five articles. Detailed information about the literature review process can be found in section 1 of the appendix.

Fig. 5a shows the NPVs for all these process specifications, which are in fact, all negative in the base scenario. Firms adopting phosphorus recovery would lose money from the investment. The different process specifications lead to a heterogenous set of NPVs. While the variation between the NPVs is low within most process specifications, the specifications of Numviyimana et al. (2020) (red) have highly differing NPVs. The recovery specifications of Lavanya and Sri Krishnaperumal Thanga (2021) (blue) and Numviyimana et al. (2021) (purple) have more stable and lower negative NPVs. That means firms implementing these technologies would lose the least money in present value terms.

The results for the levelized cost estimation are shown in Fig. 5b. They show the discounted unit production costs that is implied by the NPV estimation. The levelized cost are the necessary average price for Phosphorus to make the investment profitable. It demonstrates that the two articles with the lowest negative NPV also have the lowest levelized

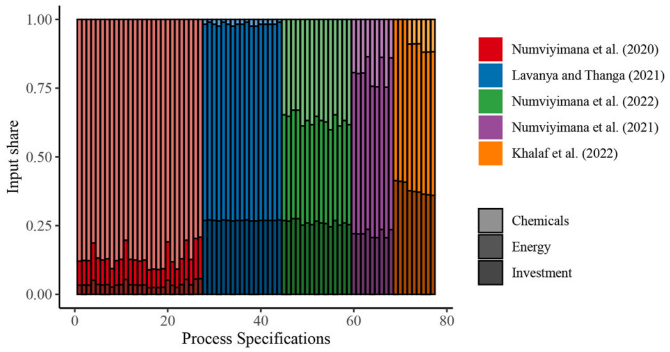

Fig. 6. Input cost shares of recovery specifications.

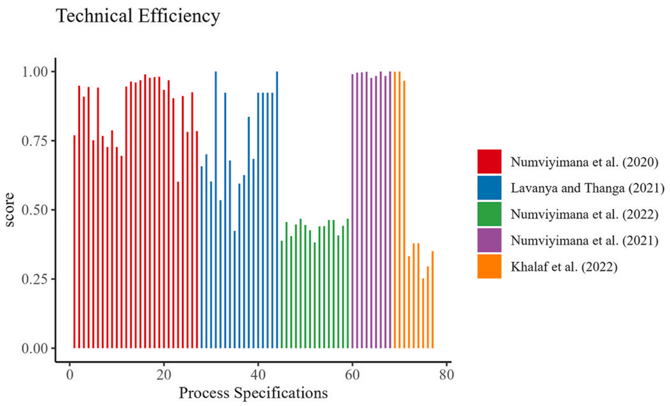

Fig. 7. Technical efficiency of Recovery Specifications.

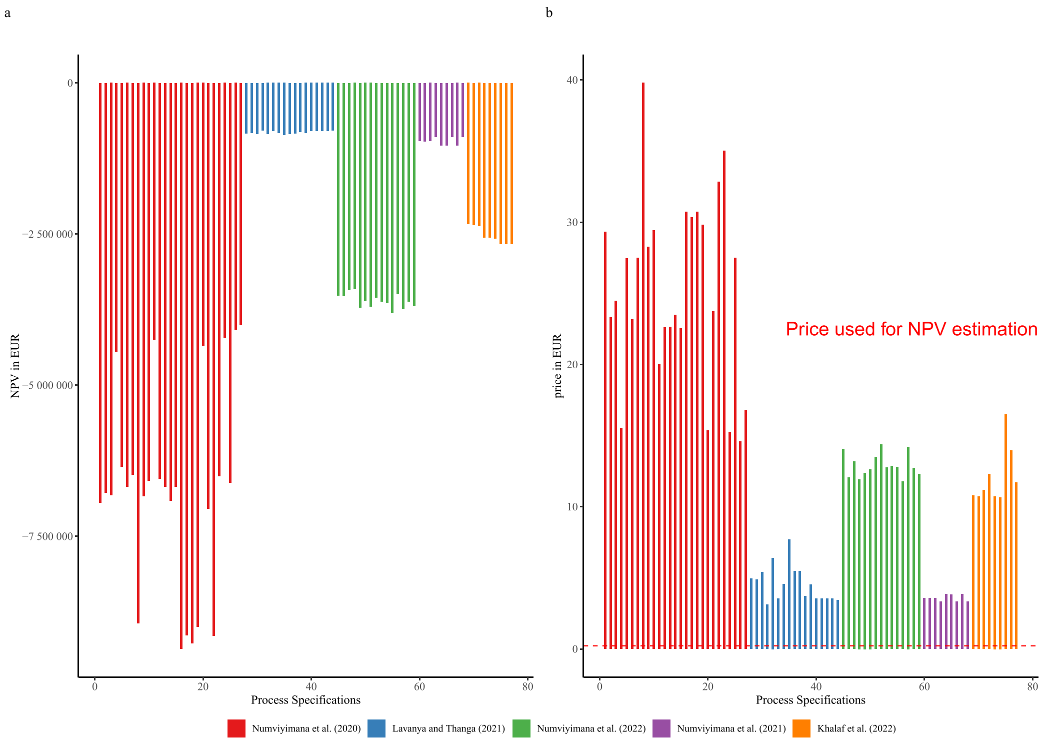

Fig. 5. (a) Net present values of phosphorus recovery specification, (b) Levelized costs of one kg of Phosphorus.

Table 3
Technically efficient recovery specifications.

Index	Source	HTC	Precipitation	NPV
31	Lavanya and Sri Krishnaperumal Thanga (2021)	0	1	−1,036,649
44	Lavanya and Sri Krishnaperumal Thanga (2021)	0	1	−1,039,019
66	Numviyimana et al. (2021)	0	1	−1,143,676
70	Khalaf et al. (2022)	1	1	−2,698,495

cost. The figure also shows that the current price of phosphorus of 0.22 EUR/kg is sixfold lower than the minimum levelized cost of 1.44 EUR/kg.

4.1. Technical efficiency

Fig. 6 shows the input cost shares of the different process specifications. In some recovery specifications, chemicals constitute the major inputs while in others the biggest input is energy. For some technologies chemicals play almost no role. For all specifications, the investment costs are a minor input.

Fig. 7 shows the technical efficiency scores of the analyzed recovery specifications. There are four technically efficient specifications (Table 3). For all four it is impossible to further reduce the use of one input, while holding the output and the other inputs constant. The efficiency estimation shows that the technology using HTC described in Khalaf et al. (2022) is technically efficient even though the NPV is much lower than for the other technologies. The technology described in the source uses hydrothermal carbonization, unlike the others, in addition to Struvite precipitation. That leads to an increase in energy and investment input but reduces the chemical input. Thus, chemical inputs are used most efficiently compared to the rest of the sample. Lavanya and Sri Krishnaperumal Thanga (2021) is the source for two frontier process specifications. This could be connected to the fact that their research objective is to optimize the process variables of phosphorus recovery. These two specifications have the highest share of energy in the inputs, demonstrating that it is possible to reduce the chemical input to produce Struvite. The mean investment is 19.3 % of the input share, highlighting the major importance of the variable costs. On the other hand, the mean input share of energy is 39.7 %.

4.2. Sensitivity analysis

The sensitivity analysis shows that most process specifications also yield negative NPVs under different scenarios (Fig. 8). However, three specifications are profitable under the scenarios that include disposal savings and high phosphorus prices. A counterintuitive result is that the scenarios with a higher processing quantity and higher sludge content have a lower NPV than the basis scenario. This is because all technologies have a negative marginal revenue with the prices in the base scenario (Appendix). The costs of recovering an additional unit of phosphorus are lower than the revenue, thus an additional kilogram of recovered phosphorus will always lead to a reduction in the profitability.

4.3. Sustainability implications

The findings of our study have implications beyond the economic interpretation. The NPV can be also interpreted as the cost of replacing sludge with recovered phosphorus. The benefits derived from this will vary depending on the damages the use of sludge as a fertilizer creates (Zamparas and Kyriakopoulos, 2021). Behjat et al. (2022) analyzed the literature of dairy processing wastewater and phosphorus recovery. The production of chemicals used in recovery is energy intensive. The relatively lower input use in technically efficient should reflect a lower resource use. As can be seen, from the change of the NPV in the crisis scenario the profitability is sensitive to a change in energy prices. For the development of new technologies, a reduction in energy use would

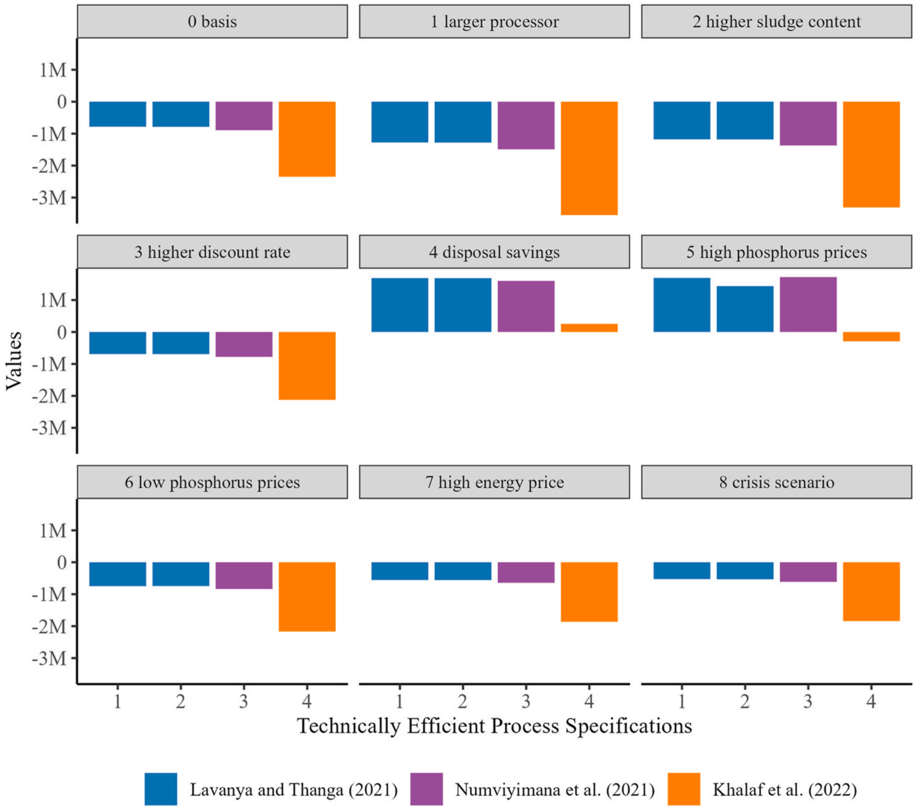

Fig. 8. NPV of the technically efficient specification in the Baseline and sensitivity scenarios.

address environmental and economic sustainability simultaneously.

5. Discussion

We reviewed the literature on phosphorus recycling from dairy processing wastewater to extract process specification on emerging technological developments. We then scaled these processes to the size of a representative dairy processing facility and calculated the profitability of each process specification. Furthermore, we estimated a technical productivity frontier and efficiency scores for the phosphorus recovery process specifications and identified those process specifications with the most efficient input/output relations. Finally, we evaluated the results for a variety of scenarios with different prices, interest rates, production quantities, material compositions and cost savings. The NPV for different process specifications and assumptions varies between 1.5 and −4.3 million EUR. For the base specifications, all NPVs of recycling phosphorus are negative and the investment is thus not profitable. However, the sensitivity analysis shows that recovering phosphorus from dairy processing wastewater can be profitable when phosphorus prices are high and/or when disposal costs are taken into account. Thus, profitability depends on general economic conditions which in turn depend on environmental regulation. Furthermore, we calculated the levelized cost of phosphorus, indicating what the cost of recovered phosphorus would need to be to make an investment break even. The levelized costs were found to be six-fold higher than the current phosphorus price.

Most studies evaluating phosphorus recovery from wastewater treatment sludge consider municipal wastewater and focus on existing applications (e.g. Daneschgar, 2019 et al.; Tonini et al., 2019). Moreover, the comparison quantified the sale of phosphorus and the purchase of the capital inputs, as these studies focus on the marginal production costs. This allows us to make a comprehensive comparison of the different technologies. For dairy processing, the recycling of phosphorus has not been implemented at scale, thus it is not possible to extract data from existing plants. We evaluated peer-reviewed articles to assess the situation for different potential technologies. Molinos-Senante et al. (2011, 2012) focus on the estimation of the NPV of phosphorus recycling by including benefits connected to the agricultural use of recovered fertilizer through reducing pollution by stopping the spreading of sludge on fields. They also take the existing phosphorus recycling technology as given and find that phosphorus recycling from municipal wastewater has a positive NPV, when including the environmental benefits of recovery. According to their calculations, a wastewater treatment plant with a capacity of 100,000 person units can generate an NPV of 171,000 EUR. While most municipal wastewater treatment plants are operated by public authorities that value environmental benefits, dairy processing is mostly a private business operation. The fact that only in very few scenarios recovering phosphorus becomes economically viable, will be a huge hurdle. Our findings are in line with Kok et al. (2018) who dampen the possible potential for phosphorus recovery to replace the production of competitive fertilizer.

Although we provide, to the best of our knowledge, the most extensive analysis of the economics of phosphorus recovery from dairy processing wastewater, the research suffers from a few drawbacks. We computed the value of the recovered Struvite fertilizer based on phosphorus equivalents. However, the secondary fertilizers may have additional beneficial or detrimental effects. The recovered phosphorus products could for instance be used as a substitute for soil amendments like peat that can receive a premium in horticultural applications (Dahlin et al., 2017). Therefore, further research should compare market traded and recovered fertilizers with a particular focus on economic benefits. Second, besides the numerous scenarios we analyzed here, a more detailed representation of risks in the underlying variables can shed further light on investment uncertainty. The large fluctuation of NPVs in the price change scenarios indicate that existing price volatility also causes volatility in profits. Previous studies have shown that volatility in profits can lead to higher discount rates (Finger, 2016) or even alter optimal investment behavior (Yanore et al., 2023). More research is needed to measure the uncertainty of cash flows of recycling investments, that can ultimately be used to model the adoption of phosphorus recycling. Third, in this study we only implicitly considered the role of regulations in the adoption through the disposal costs. While we find that these regulations might have large effects on the profitability, a detailed assessment of further policies such as investment subsidies or guaranteed fertilizer prices would be an interesting objective for future research. Fourth, the up scaling from experimental data leaves room for potential economies of scale in the actual implementation. What we show is what the currently available technologies can achieve. However, some choices in the analyzed experiments might not have been intended for full-scale application. Accordingly, some of the experiments were designed to demonstrate chemical effects in small batches, they might have been designed differently if they were intended to be scaled up. If an experiment is primarily implemented to show a chemical effect, researchers might use a more expensive but marginally more effective input, of which the potential saving should be explored in future research. A number of studies could not be included in the review due to lacking information. To allow an economic comparison, technological studies should strive to include complete data on the material flow. Moreover, technical research would benefit from describing the potential applications. Moreover, the efficiency analysis relied on the assumption of the absence of economies of scale, which allowed us to assume the processes could be scaled up.

Society would benefit from implementing the recovery from phosphorus recycling. First, because less resources will be wasted. Second, current polluting sludge spreading practices can be improved by recovering fertilizers, thereby improving the environmental performance of the agricultural sector (Ashekuzzaman et al., 2019). The implementation of phosphorus recycling might therefore be supported by policy instruments. The EU has set strict environmental targets aiming to integrate the circular economy into environmental regulation (European Commission, 2020b). We observe that all of the proposed technologies in the base scenario have a negative variable profit. Therefore, the variable costs per unit of phosphorus are a major barrier to profitability. We observe that for hydrothermal carbonization, energy costs make up a large part of these variable costs. Struvite precipitation conversely uses a lot of chemicals. In other words, phosphorus recovery requires a large amount of inputs and there is a clear trade-off between resource use and the reduction of pollution through phosphorus recovery. There is a need for research that highlights how inputs can be reduced in chemical recycling and how to balance conflicting policy targets. Technology subsidies should be appropriately targeted by either corresponding to the reduction of externalities (Molinos-Senante et al., 2012) or targeting the potential for improvement in the technology through innovation. The analysis of economic costs and benefits of phosphorus recycling is therefore a crucial decision support for policymakers, potential investors and technology developers. To the best of our knowledge, the here proposed combination of a systematic literature review to identify the most promising technical processes, profitability assessments of these using the Net Present Value approach, and Data Envelopment Analysis to determine most efficient processes is novel, and applicable to other recycling investment decisions. We therefore suggest future research to follow our methodology.

6. Concluding remarks

The analysis interpolates innovative technology concepts at the scale of a possible application. This approach allows us to make claims broader than the technology application. From the results we are able to highlight trade-offs between several technologies. The quantification of the inputs allows us to critically put the chemical and energy use in relation to the produced phosphorus. The efficiency measurement highlights technologies that can reduce resource use. Future research on recovery applications should further scrutinize the assumptions of this research.

These trade-offs between off-setting pollution and reducing energy consumption create barriers for the adoption of phosphorus recovery and should be considered by policy makers and investors. More specifically, policy makers might make supporting policies for phosphate recovery conditional on renewable energy use. Vice versa, investors should consider additional investment risk when opting for non-renewable energy use for phosphate recovery, which might be increasingly regulated.

To conclude, we provide the first evidence of the profitability, or lack thereof, of recovering phosphorus from dairy processing wastewater. While phosphorus recovery can play a role in the transition of the dairy sector to a more circular system, the economic reality needs to be taken into account and—where possible and desirable—addressed by tailored policies.

CRediT authorship contribution statement

Jan-Philip R. Uhlemann: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Alfons Oude Lansink:** Writing – review & editing, Methodology, Conceptualization. **James J. Leahy:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Tobias Dalhaus:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jan-Philip Uhlemann reports financial support was provided by the European Union. Theother authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is available at a repository accesible through a link in the manuscript

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120606.

All data generated in this study are available in the following open access repository: https://github.com/jpu585/Do-investments-in-phosphorus-recovery-from-dairy-processing-wastewater-pay-off- and can be cited using the following DOI: 10.5281/zenodo.10074655.

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