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Improving the homogeneity of a sewage sludge-based phosphorus fertilizer by Monte Carlo simulation of the production chain

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Abstract Sewage sludge mono-incineration with subsequent phosphorus (P) recovery from the ash is becoming increasingly important in many European countries. Plant operators are facing the challenge to produce a homogeneous P output which needs to conform to fertilizer standards (including trace elements levels) upon processing. This needs to take into account (i) the compositional variability of municipal sewage, (ii) design of incinerator and phosphorus recovery unit, and (iii) logistical and management aspects. In this study, those challenges were considered in Monte Carlo simulations based on a discretized sewage sludge input. To propagate the uncertainty along the entire process chain of thermal sewage sludge treatment and P-recovery, a simulation model was implemented using MATLAB. Specifically, logistical factors, different management options along the treatment chain, technical boundary conditions were investigated and the distribution of the P_2O_5 concentrations in the output (fertilizer/ash) was calculated. The results show how appropriate handling and treatment of sewage sludge helps to reduce the width product properties (e.g. P_2O_5 distribution, trace metal distribution in the output. From the options tested, storage management (including automated crane operation) had the strongest homogenization effect and could be easily implemented at incinerator sites. **Keywords: sewage sludge ash, Monte-Carlo-simulation, risk analysis, phosphorus recovery**

1. Introduction

Secondary P resources are importantly linked to municipal sewage systems since, globally, around 1.3 Mt of P per year are treated in wastewater treatment plants (Li and Li 2017) and are ultimately absorbed into sewage sludge. In view of exploitation of this secondary P resource, the 2017 amendment of the German Sewage Sludge Ordinance (Anonymous, 2017) demands that large wastewater treatment plants (WWTP) recover P from process streams by 2029, while a direct agricultural application of dewatered sludge becomes increasingly restricted (Hudcová et al., 2019). Similar legislative approaches are currently in discussion in various European countries. This is currently fostering the implementation of pertinent technologies. Many of these focus on the recovery of P-fertilizers from sewage sludge ash (SSA) since in terms of P-levels, these are comparable to as to medium to high-grade phosphate ores (Weigand et al. 2012).

Considering economies of scale, combined sewage sludge combustion and P-recovery is likely to take place at centralized plants that use the sewage sludge from a series of individual WWTPs (Cieślik und Konieczka, 2017). Under these conditions, plant operation is challenged by the physicochemical variability of the input. Important sludge features like calorific value, loss on ignition, or elemental composition can be expected to vary among WWTPs (e. g. due to process layout) but also for each individual WWTP (e. g. due to seasonality effects). Sewage sludge variability directly translates into ash and product variability. The latter is particularly conflicting since the recovered P-fertilizer needs to conform to regulatory specifications in terms of trace elements levels (Chanaka Udayanga et al. 2018) and P content (e.g., the German Fertilizer Ordinance (Anonymous, 2008) specifies permissible tolerances depending on the targeted fertilizer product of no more than 1 to 2 % points). A complete survey of the German SSA showed that the P concentration of SSA varies greatly from plant to plant (up to 5 wt.%) and over the year (Krüger et al., 2014).

This study, aimed at investigating the variability of sewage sludge properties on the regional scale and its effects on the composition of the recovered P-fertilizer. A Monte Carlo-based stochastic model was developed to provide an integral picture of sewage sludge logistics and storage management, mono-incineration and phosphorus recovery from the ash. The model input considered the compositional variability of sewage sludge on a regional scale.

2. Methods

2.1. *Data acquisition and handling*

The study region is located in central Germany and comprises 57 WWTP, each serving between 150 and 300,000 population equivalents (PE), where 1 PE corresponds to 60 g BOD /(capita · day). The average amount of raw sewage sludge in the study region amounts to 121,000 t/a. A survey was undertaken regarding WWTP size, technological equipment, sewage sludge generation as well as sludge physico-chemical properties including dry matter contents (DM), loss on ignition (LOI) as well as P and trace metal contents. In total, 532 data sets of the regional sewage sludge were compiled. Some WWTP operators provided complete data with information for the past three years, but for a considerable number of WWTP only incomplete data was available.

The data was used to derive WWTP-specific triangular probability density functions (PDF) for each of the sewage sludge parameters to be used in the Monte Carlo simulations. This pragmatic approach was chosen since it allows for the representation of skewness in spite of the limited amount of data. Missing data were compensated by specific regression imputation (Kang, 2013) to generate a complete set of input distributions.

2.2 *Model description*

In order to map the uncertainty along the entire process chain of sludge storage, incineration and P recovery and to investigate the influence of individual process optimization steps, a model was developed with MATLAB R2021b (Mathworks, Inc) that represents real life industrial plant for thermal treatment of sewage sludge and P-recovery from the resulting ash.

The model input considers the annual amount of dewatered sludge from the 57 WWTPs and the PDFs generated as described in section 2.1. The PDFs were discretized by dividing the total dewatered sewage sludge into individual packages of 100 kg each. The 977,531 packages (sewage sludge packages, SSP) generated in this way represent the annual sludge supply and were stored in a data field (basic population). Each SSP was labelled by origin. This allowed to randomly assign sewage sludge properties from the corresponding PDF. Specifically, individually SSP were randomly drawn from the population and the respective property expression (TS, OS, P_2O_5, Cu, Pb, …) was randomly assigned based on the associated WWTP-specific triangular PDF.

The logistics implemented in the model take into account the fact that deliveries are not made in the form of individual SSPs, but by truckloads comprising 250 SSP. We assumed mono deliveries from a specific WWTP, whereby the SSP-properties differed per truckload depending on WWTP and within each delivery according to the stochastic allocation. Based on projected incinerator throughput (25 t/h), 24 trucks deliver a total of 600 t of sewage sludge per simulation day. All steps between delivery and thermal treatment of the sewage sludge were implemented in a storage management system. This consists of a bunker with crane removal system and a parceled transfer platform for feeding the individual incineration lines. The bunker is simulated by a data field with a capacity of 10,000 SSP (1,000 t). The 250 SSP of each truck delivery are written into the data field in a constant order (250 column entries). Mixing effects during the unloading of the truck units into the bunker were not considered. This is supported by the results of a full-plant investigation by Fellner and Schwarzböck (2021). Based on the real process, an automated removal and rearrangement of the bunker contents is simulated to produce a more homogeneous input mixture (Mackin and Fujiyoshi, 2018). To simulate crane operation for mixing, the data field was divided into 20 predefined areas, each containing 500 SSP and a simple algorithm for SSP removal and rearrangement was implemented. The removal quantity was 50 SSP, corresponding to 5 tons grab bucket. Every simulation day, the grab delivers a total of 6,000 SSP (120 bucket loads). These are taken evenly from each of the 20 predefined areas of the storage data field. Between each daily extraction, the crane performs grab and drop operations to redistribute some of the bunker contents (6,000 SSP) within the 20 predefined areas and provide mixing. Real crane systems run similar programs to optimize the topography of the waste fill in the bunker and to achieve homogenization of the material (Mackin and Fujiyoshi, 2018).

After withdrawal and redistribution, the withdrawn quantity is replaced by a new truck delivery of 250 SSP. For this purpose, the gaps in the data field caused by the random sampling were first closed by moving the entries up. Finally, the new SSPs are added at the end of the data field. The quantity of 250 SSP taken from the bunker is then conveyed to the so-called transfer platform. This represents an interim storage facility (transfer platform, Figure 1) and is in turn divided into 4 different areas, each with a capacity of 40 t (400 SSP).

The input for each fluidized bed combustion line is generated by merging two sections of the transfer platform. At the real plant this is done with a conveyor belt.

According to the plant operator the residence time of the sludge in the fluidized bed is about 10 seconds. We assumed that there is always just one SSP in the combustion chamber and that no mixing occurs.

During the simulated combustion, the organic content is removed from each SSP. Ignoring volatilization, inorganics would accumulate in the ash in proportion to dry matter (DM) contents and loss in ignition (LOI) of the SSP resulting in specific ash contents (c_i):

$$m_{SSA} = m_{SSP} \cdot DM[\%] \cdot (1 - LOI[\%]) \quad (1)$$

$$c_i = \frac{m_i}{m_{SSA}} \quad (2)$$

This way sewage sludge ash packages (SSAP) are generated from the SSPs and subsequently stored in the ash silo data field, which simulates the ash storage of the real plant. The data field is filled alternatingly with a SSAP from the two incineration lines. When a set upper limit is reached, the silo is emptied, and the ash is fed into the P-recovery process.

The P-recovery shown in the simulation comprises two process steps, (i) acid digestion in a batch stirred reactor and (ii) a spray granulation of the digestate. We assumed that neither process affects the element content of the ash or the fertilizer produced. The only considered process variable in our model was the batch size going into acid digestion during which a perfect mixture of the batch input was assumed. Thus, the elemental composition of the final product results from the properties of the individual SSAPs comprising the respective batch.

The average composition of each batch is calculated and stored in the batch matrix at the end of each simulation run. Finally, the model output is evaluated as a histogram.

2.3 Model scenarios

To investigate the effects of different process configurations on the probability distribution functions of the output parameters, several process scenarios were tested (see Figure 1).

Scenario 1 describes a variant in which the entire basic population of sewage sludge is incinerated without applying any supply logistics or storage management.

Instead, the individual SSP are fed to the incineration process and the SSAP are calculated with eqns. (1) and (2), resulting a distribution of ash properties. Consequently, there is no mixing along the process. The resulting distribution thus fully retains the heterogeneity of the input sewage sludge form the region.

In Scenario 2, P recovery is added as an additional step so that the randomly generated SSAP is batch-wise processed into a product. The resulting parameter distribution is therefore affected by mixing on the batch scale.

Scenario 3 includes the supply logistics (truck delivery) and reflects the fact that the packages do not arrive at the entrance to the treatment plant in random order but in truckload quantities from individual WWTPs.

Scenario 4 ultimately adds storage management to the treatment process as described in section 2.2.

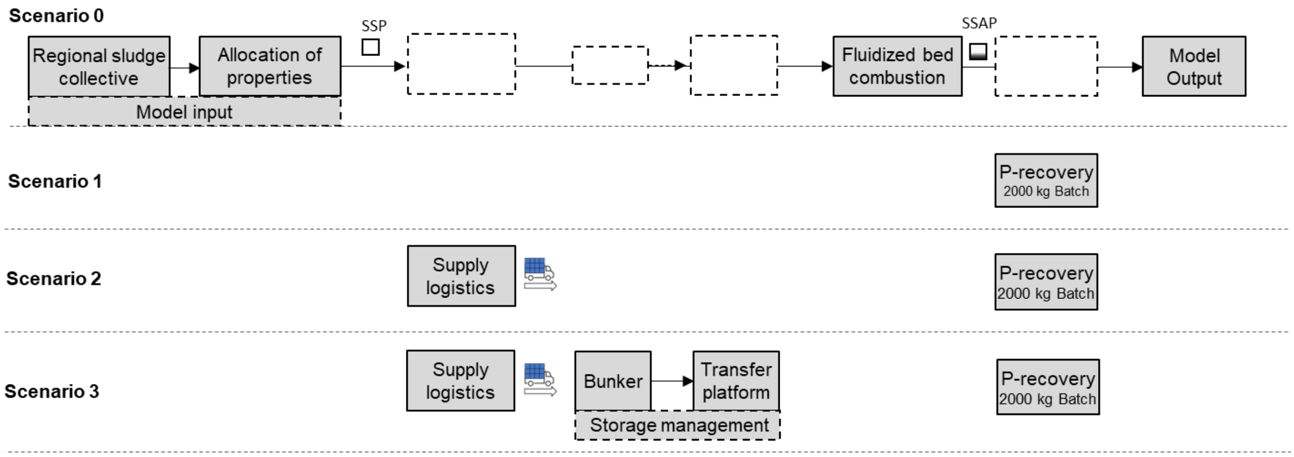

Figure 1. Schematic illustration of the scenarios considered. Scenario 0 reflects the basic model and for scenario 1-3 only the additional model components are shown.

3. Results and discussion

The developed model was applied to four different scenarios and the distributions of the P_2O_5 concentrations in the output (fertilizer/ash) were calculated. Figure 2 shows the model output in the form of probability distributions. Scenario 0 represents the distribution of the population of all SSP and is therefore, as expected, very broad and multimodal. This is because there is no mixing in the simulation of the basic population and the entire range of the concentrations is mapped, which illustrates the challenge of producing a homogeneous fertilizer from sewage sludge collected from a larger region having a collective of WWTPs. In contrast, scenario 1 represents an idealized case. While maintaining the random delivery of individual packages, these are now processed into batches of 2000 kg during the P-recovery step which results in a much narrower distribution compared to scenario 0. The resulting distribution is very hypothetical considering that random delivery of individual packages as system input is not feasible in practice. Nevertheless, the legally required tolerances of the German Fertilizer Ordinance can only be maintained within a fluctuation range of one percentage point. Clearly, a broader distribution is observed when a realistic delivery by truck units is considered in scenario 2. The multimodality results from the higher probability of selecting larger wastewater treatment plants during the simulation. This leads to distinguished peaks and causes a discrimination of the edge concentrations scenario 0. Altogether scenario 2 highlights the challenges associated with delivery logistics and underpins the need for a storage management prior to incineration/P-recovery. The latter was implemented in scenario 3. With a bunker storage and homogenization crane pick and drop and using the transfer platform as a secondary mixing opportunity, a unimodal distribution results as in scenario 1. However, compared to scenario 1 (ideal case) the distribution is much broader and further measures are required to achieve a reproducible fertilizer composition. Current work includes consideration of the scenarios presented here and their implications for the distribution for various critical trace metals. For example, it is being examined whether a sewage treatment plant-specific separation or an injection of external sewage sludge is target-oriented for compliance with legal requirements.

4. Conclusion

The results demonstrate prominent effects of the individual model components and prove the suitability of the Monte Carlo simulation for depicting the product heterogeneity in P-recovery from SSA. As a next step, individual model components will be varied in a targeted manner in terms of their influence on the output distribution. Alternative storage management concepts will be developed and implemented into the model to investigate their effect on output quality.

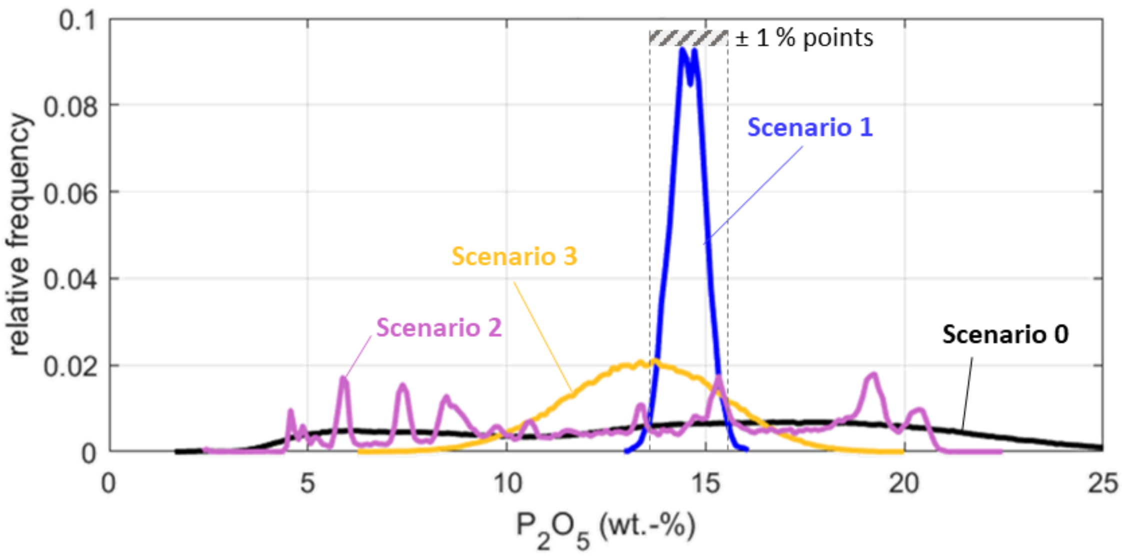

Figure 2. P_2O_5-Distribution of the model outputs for the four scenarios. Scenario 0 (black), 1 (blue), 2 (magenta) and 3 (yellow)

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