Reducing sewage sludge ash variability in the context of P-recovery by optimizing the storage management using Monte-Carlo simulations

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Abstract Phosphorus (P) is a critical raw material and the EU largely depends on P-imports to cover its demand. This is increasing efforts to recover P from secondary P-sources such as municipal sewage sludge ashes (SSA) from mono-incineration. Usage of SSA for mineral fertilizer production requires compliance with certain quality standards regarding P-concentrations and trace element levels. This is particularly challenging in view of the variability in composition and amount of sewage sludge due to different technologies applied by the wastewater treatment plants (WWTP) and various catchment areas when sludge is jointly incinerated. By applying different sewage sludge treatment processes along the process chain, homogenization of the output quality of mono-incineration plants may be achieved. To investigate the effects of input variability and treatment processes on SSA composition a Monte-Carlo simulation approach was used. The simulations included probability distributions of sewage sludge composition data from 57 WWTP. Missing data were compensated by mean substitution to generate a complete set of input distributions. The resulting distributions of SSA nutrient and contaminant concentrations obtained by the simulation were compared.

Keywords: phosphorus, P-recovery, Monte-Carlo-simulation

1. Introduction

Phosphorus (P) is an essential nutrient and necessary for food and feed production. In 2018, 249 Mt of phosphate rock (PR) were mined worldwide and primarily used to produce fertilizers for agriculture (US Geological Survey 2020). Since 2014, the European Union considers PR a 20 critical raw material (European Commission 2014). Thereby accounting for the concentration of mineable deposits to only a few countries and Europe's almost complete dependency on P imports. Globally, around 1.3 Mt of P from sewage discharge are annually treated in wastewater treatment plants (Li and Li 2017). Most of it is transferred to the sewage sludge which may thus be considered an important secondary P-resource (Yuan *et al.* 2012). In this light, the 2017 amendment of the German Sewage Sludge Ordinance demands that large WWTPs recover P from process streams by 2029, while a direct agricultural application of dewatered sludge becomes increasingly restricted (AbfKlärV 2017). This is currently fostering the implementation of pertinent technologies with a strong emphasis on the processing of sewage sludge ash (SSA) to P-fertilizers owing to the fact that P in SSA reaches levels indicative of medium to high-grade P-ores (Weigand *et al.* 2012). For an economic operation, such incinerator/recovery plants would typically need to be centralized requiring the input of sewage sludge from a series of individual WWTP. Under these conditions, product specifications of the recovered P-fertilizer are challenged by the compositional and physical variability as well as possible fluctuations of the input sludge. This needs to be accounted for (and potentially be minimized) by the sewage storage management at the incinerator/recovery plant. Doing so, the variability of input properties may be adequately described as a random process constrained by the parameter distributions that characterize the sludge of each of the considered WWTP. In this study, the variability of sewage sludge properties on the regional scale and its effects on the composition of the recovered P-fertilizer were considered in Monte-Carlo simulations. This simulation technique is based on offsetting simulated random events that are generated from parameter distributions (Berthouex and Brown 1994; Vose 2004). Therefore, a stochastic model was developed that represents two different P-recovery treatment processes. Using actual sewage sludge composition data acquired from 57 regional WWTP the composition and trace metal concentration of fertilizer derived from sewage sludge ash was simulated.

2. Methods

2.1. Data acquisition and handling

Composition data for sewage sludge was derived from wastewater treatment plants (WWTP) located in central Germany. The study area is characterized by a small-scale interlocking of rural and urban areas with many clusters of smaller industries. Overall, data from 57 WWTP was considered in this study. These include plants in municipalities with a direct connection to agricultural areas, as well as large sewage treatment plants in urban settings.

The amount and characteristics of the individual sewage sludges were retrieved from i) the answers to a questionnaire sent to the WWTP operators, ii) the official sewage sludge data collection of the pertinent Administrative Council and iii) more comprehensive data sets provided by several WWTP operators. A total of 532 (partially incomplete) data sets of the regional sewage sludge were compiled, including information on P-levels, dry matter (DM), loss on ignition (LOI), trace metals and others over the past three years.

Missing data was compensated by mean substitution (Kang 2013) to generate a complete set of input distributions.

The WWTP were grouped and parameter-specific distributions for plants with ≥ 5 data sets were calculated. Tests for the goodness-of-fit (chi-square and Anderson-Darling) were performed for various distributions. Triangular distributions were used as both tests provided satisfactory fit and such distributions are easy to handle.

The ranges of the derived triangular distributions were used to impute similar distributions for WWTP where less data was available. Mean or single values available for those WWTP served as peak values of the triangular distributions, while the ranges were imputed.

2.2 Description of the recycling process

For the Monte-Carlo simulation, a sewage sludge treatment process (SSTP) was dimensioned (Figure 1) to treat an annual amount of approx. 98,000 t mechanically dewatered sludge (≥ 20 wt.-% DM). The SSTP comprises I) storage, II) drying, III) scenario-specific treatment (incineration, ash storage and P-recovery) with a plant throughput of 12 t/h. The storehouse has a total capacity of 4,000 kg. For sewage sludge drying to a target value of 40 wt.-% DM a conventional industrial belt dryer is projected, which provides only little mixing during sludge passage. The energy consumption for sludge drying was estimated based on Ledakowicz et al. (2019). For incineration of the dried sludge and subsequent fertilizer production, two scenarios (A and B in Figure 1) representing different recovery approaches were considered.

Scenario A represents fluidized-bed combustion of the sludge combined with wet digestion/acid leaching process of the ash (Cieślik and Konieczka 2017; Egle *et al.* 2015; Weigand *et al.* 2013). In the latter ash batches of 2,000 kg are treated in a batch-operated stirred tank reactor (BSTR) providing ideal mixing.

The thermochemical process (scenario B) comprises sequential pyrolysis, incineration and thermochemical treatment (Ledakowicz *et al.* 2019). The latter serves to partially volatilize trace elements and increase the plant-available P in the residue. All steps are performed in a rotary kiln with only minor axial dispersion. Therefore, this scenario is implemented with a smaller batch size of 133 kg.

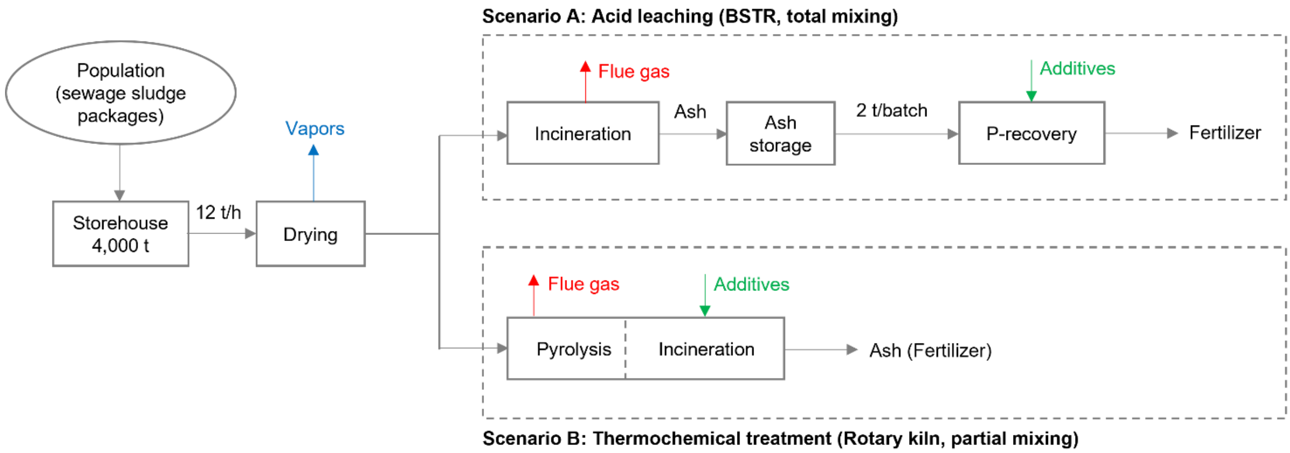

Figure 1. Schematic of the projected SSTP for two scenarios (A: acid leaching, B: thermochemical treatment) for P-recovery

2.3. Model overview

The described treatment and recovery process was implemented in a computer model using MathWorks MATLAB. The annual amount of sewage sludge was considered the statistical population which is described by the derived distribution data.

For each WWTP the annual amount of sewage sludge was split into sewage sludge packages (SSP) of 100 kg each, therewith considering the statistical population. Package properties were randomly picked from the specific triangular parameter distributions of each WWTP.

Simulating the combined drying and incineration process the SSP were converted to sewage sludge ash packages (SSAP) considering DM and LOI (equation 1). Each SSP and SSAP is implemented as a matrix of components (e.g. P-levels or Cu-levels as a surrogate of trace metal content). The concentration in the SSAP is calculated as the ratio of the components mass (m_i) in the corresponding SSAP and its mass (m_{SSAP}, equation 2) considering the LOI of the underlying SSP.

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

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

A number of SSAP equivalent to the batch size of the P-recovery processes was sampled from the SSAP collective and homogenized. For each batch, the mean value was calculated from the individual SSAPs collected within the batch.

The Monte Carlo simulation was run to treat $1.2 \cdot 10^6$ packages which correspond to the amount of sewage sludge of 12 years of operation.

3. Results and Discussion

The developed model was applied to two different scenarios for P-recovery and the distributions of the P_2O_5 and Cu concentrations in the output (fertilizer/ash) were calculated. Figure 2 shows model results for the statistical population and the two scenarios (A: acid leaching, B: thermochemical treatment).

The distribution of the basic population for both P_2O_5 and Cu concentration is 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.

The mean P_2O_5 concentration of the basic population is 14.56 %, the mean Cu content is 543 mg/kg.

Without mixing, many ashes would exceed the limits of the EU Fertiliser Ordinance (EU) 2019/1009.

Scenario A provides a much narrower distribution than scenario B. The reason for this is the larger batch size and the total mixing within the BSTR. By increasing batch size the intrinsic heterogeneity of each SSAP is compensated. The distribution of the Cu concentration obtained for scenario A shows that the output fully complies with the EU limit value for fertilizers.

A smaller batch size was selected for scenario B to reflect the lower dispersion and, hence, mixing performance in the applied rotary kiln. Compared to scenario A this results in a broader distribution of both the contents of P_2O_5 and Cu.

In this case, a certain proportion of the output exceeds the EU limit value. Thus, additional process steps would be necessary to increase the overall mixing within the SSTP and comply with the limit values. This is the case when Cl-donors are added to the kiln process to volatilize trace elements and yield depleted ash.

With a sufficient batch size, storage of the ashes in several content classes and targeted mixing of the ashes, the limit value in scenario A could be complied with.

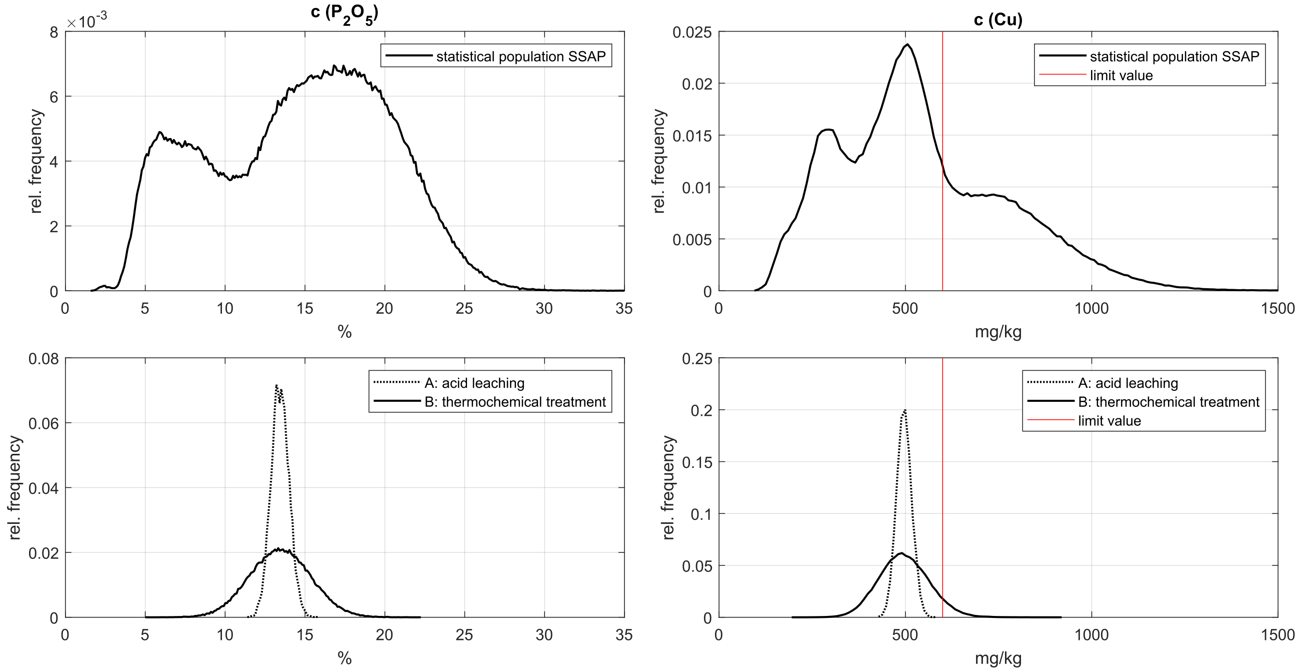

Figure 2. Distribution of P_2O_5 and Cu in the statistical sewage sludge ash population and the model outputs for the two scenarios (A: acid leaching, B: thermochemical treatment).

Finally, several potential limitations need to be considered. In the model, we assumed that the entire annual sewage sludge mass is continuously available to allocate the SSPs randomly in the storehouse throughout each year of operation. Therefore, it cannot represent the discontinuity of various parameters due to logistical constraints. In addition, the storehouse cannot be completely emptied. The probability of drawing a certain SSP is always the same so that the storehouse always represents only a quantity-weighted distribution.

4. Conclusion and Outlook

In this study we developed a stochastic model to evaluate the composition and trace metal concentration of fertilizer derived from the sewage sludge ash collected on a regional scale. For the SSA statistical population of 57 WWTPs, broad distributions of P_2O_5 and Cu concentrations were attained.

The latter indicates that mixing is required to receive a homogeneous product that complies to limit values on the one hand and to product specifications on the other. The key variable in our model is the batch size which undergoes a total mixing. This aspect is of particular importance since batch sizes differ strongly across sewage sludge treatment processes.

In future research, different storage management concepts will be developed and implemented into the model to investigate their effect on output quality. Furthermore, process intrinsic mixing during drying and incineration (fluidized bed) will be implemented in terms of a dispersion coefficient for the individual treatment steps. To reflect the fate of trace metals along with the SSTP, elimination steps based on literature values (scenario A: precipitation step during acid-leaching, scenario B: volatilization by additive addition) will be implemented.

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