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Techno-economic and environmental assessment of upgrading alternatives for sludge stabilization in municipal wastewater treatment plants

Maria Concetta Tomei [a,*], Giorgio Bertanza [b], Matteo Canato [b], Sara Heimersson [c], Giuseppe Laera [d], Magdalena Svanström [c]

[a] Water Research Institute, C.N.R., via Salaria km 29.300 C.P. 10, Monterotondo Stazione, 00015 Rome, Italy
[b] Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, via Branze 43, 25123 Brescia, Italy
[c] Department of Chemistry and Chemical Engineering, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
[d] Water Research Institute, C.N.R., viale De Blasio 5, 70132 Bari, Italy

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A B S T R A C T

In this work we have performed a feasibility study of two upgrading alternatives for sewage sludge stabilization aimed to the reduction of the produced sludge and to the improvement of its qualitative characteristics with respect to its final destination: agricultural use or incineration. The first upgrading (1) proposes the separated thickening: primary sludge is thickened by gravity while dynamic thickening is applied to secondary sludge. The second upgrading (2) introduces a post-aerobic digestion stage (after the anaerobic one), in addition to separate thickening. Technical-economic and environmental assessments have been performed in comparison to a conventional wastewater treatment plant, which operates with gravity thickening and anaerobic digestion of mixed sludge. In the post-aerobic stage, operated with intermittent aeration, additional volatile solids removal of 45% and nitrification and denitrification efficiencies of 97% and 70%, respectively, were achieved. Both upgrading alternatives gained a positive technical evaluation with the only exceptions of the item "*Thermal energy consumption*" in upgrading 1 for agricultural reuse, and, to a minor extent, the "*Energy available for external recovery*" for incineration in both upgrading options. Cost analysis showed that the two upgrading alternatives are generally cheaper than the conventional plant, even if the results are dependent on local conditions, which have to be considered. Results of the environmental assessment showed that the upgrades with incineration perform better than the reference for all impact categories except freshwater eutrophication, with upgrading 2 as the best option. For the agricultural use, different results were obtained for the different impact categories with critical aspects mainly related to phosphorus and ammonia emissions for upgrading 1.

1. Introduction

As generally recognized, sludge stabilization is a key operation unit of the sludge treatment line, strongly affecting the quantity and quality of the produced sludge. Effective and controlled stabilization is fundamental in optimizing and "tailoring" the sludge characteristics to match the needs of the final destination. In spite of the relevance of the sludge line in determining the overall performance of wastewater treatment plants (WWTPs), more attention has traditionally been paid to the design of the water line. This is well demonstrated by the extensive work previously done on WWTP modelling mainly focused on the biological section of the plants, as for example in the IWA Activated Sludge Models (Henze et al., 2000). There are no analogous detailed models available for the sludge treatment units in the scientific literature. In recent years, the sludge line has received an increasing interest, both in terms of optimization of plant performance and cost reduction because, as reported in Mininni et al. (2015), the costs of treatment and sludge disposal account for up to 50–60% of total operating costs of WWTPs. However, while new

* Corresponding author. Tel.: +39 0690672800; fax: +39 0690672787.
E-mail address: tomei@irsa.cnr.it (M.C. Tomei).

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WWTPs are designed using criteria that will render it possible to achieve high performances also in the sludge treatment line (e.g. applying effective control strategies, technological solutions for enhancing sludge stabilization, and maximizing the energy and resource recovery), the situation of older WWTPs is more critical and they often require upgrading measures, especially for the sludge line.

The holistic assessment of new technologies for sewage sludge treatment involves several aspects (economic, environmental, technical, social, etc.) and stakeholders (decision makers, plant managers, citizens). As a further source of complication, many involved factors are completely qualitative, so that they cannot be directly measured or quantified; this is the case of externalities which "refer to any consequence (positive or negative, intentional or random) that derives from a project" (Hernández-Sancho et al., 2010). While economic analysis methodologies, typically based on the tools of the capital budgeting analysis (e.g. payback, accounting rate of return, internal rate of return and net present value) (Schall et al., 1978), are consolidated and widely used (see for instance Mills et al., 2014; Brunner and Starkl, 2012 and Jolly and Gillard, 2009), many challenges still remain for the quantification of the externalities, as pointed out by Molinos-Senante et al. (2010). As a consequence, in several cases the decision making process omits externalities, following a simplified approach focussing only on a single or a few aspects (e.g. either costs calculation, or environmental impact, or social aspects, etc…) as pointed out in the review of Achillas et al. (2013). Notwithstanding, the integrated assessment of environmental technologies (i.e. cost-benefit analysis) has to be performed, as also requested by the WFD (Water Framework Directive 2000/60/EC). In our proposal, the cost-benefit analysis is carried out by attributing a common ranking to all the evaluation factors (both techno-economic and environmental), thus overcoming the critical (if not impossible) economic quantification of those factors that are not typically valuable because they are not marketable. In particular, as for environmental aspects, within the applied integrated assessment methodology, a life cycle assessment (LCA) analysis has been performed. LCA has been a common tool for assessing environmental impacts of wastewater and sludge management systems, see e.g. reviews by Corominas et al. (2013) and Yoshida et al. (2013). LCAs can be used to shed light on for example environmental hot spots in studied systems (in terms of e.g. dominant activities or dominant emissions) and to compare the environmental performance of different systems.

In this paper, we proposed and analysed two upgrading alternatives for sludge stabilization aimed at both reducing the amount of produced sludge and improving its characteristics with respect to its final destination.

The reference plant is a conventional urban WWTP including gravity thickening and anaerobic digestion of mixed primary and secondary sludge. The first upgrading introduces separated sludge thickening for primary and secondary sludge, while the second upgrading introduces a post-aerobic sludge digestion, in addition to separate thickening. The two proposed upgrading alternatives were each studied with two possible final destinations of the sludge: agricultural use and incineration. We excluded landfill due to the more and more stringent limits imposed on this practice as well as the intrinsic drawbacks connected to this disposal option (e.g. gaseous emissions which contribute to global warming, hazardous compounds in leachate to be treated, nutrients and organic matter lost). Agricultural use was selected as one scenario because of the positive effects (many of them are reported in García-Gil et al., 2004) related to the application of sludge on the soil (primarily, sludge reintegrates the progressive loss of organic matter and nutrients in soils) and because it is expected to remain a major option in the future for many countries (Gianico et al., 2013). However, in many EU countries this disposal option is forbidden, mainly due to the potential risks associated with the presence of pathogens and micro-pollutants such as heavy metals and organics (Gianico et al., 2013). In many EU countries, incineration is one of the most applied disposal options in spite that it is considered a cost intensive process (Foladori et al., 2010). It also leads to the loss of valuable matter present in the sludge, but both energy and phosphorus can potentially be recovered. However, phosphorus recovery was not considered in this study to avoid a split focus as this is also a technology under development.

As secondary sludge is characterized by lower settleability and dewaterability (Bertanza et al., 2014) in comparison to primary sludge, the separate treatment of primary and secondary sludge allows for dynamic thickening of secondary sludge (Mininni et al., 2004). This process has a higher efficiency than gravity thickening and results in increased solid concentration of the thickened sludge. The expected advantages are related to the higher organic load rate (OLR) in the subsequent anaerobic digestion, which results in increased biogas production and enhanced digester performance.

The introduction of a post-aerobic stage with intermittent aeration after the anaerobic digestion is expected to increase the removal efficiency of the volatile solids (VS) due to the additional degradation of the solid fraction not (or only modestly) degraded under anaerobic conditions (Kumar et al., 2006; Tomei et al., 2011), and to achieve the nitrogen removal in the supernatant through alternating anoxic–aerobic cycles (Zupancic and Ros, 2008; Parravicini et al., 2008; Tomei and Carozza, 2015).

The present paper reports on the technical, economic and environmental assessment of the three proposed sludge treatment layouts, performed according to the methodology described by Bertanza et al. (2015) and Svanström et al. (2014). This study aims at providing a detailed and exhaustive comparison of the proposed upgrading options, based on the integration of experimental data, plant modelling and mass and energy balances.

2. Material and methods

2.1. Reference plant and investigated scenarios

The reference plant capacity is 70,000 person equivalents (PE). The plant layout includes preliminary treatment, primary settling, a biological section (anoxic and aerobic bioreactors), and gravity thickening of the mixed sludge, followed by anaerobic digestion. The plant is equipped with a combined heat and power (CHP) system for heat and energy recovery from the biogas produced in the anaerobic digestion. Effluent is discharged in a non-sensitive area.

In the first upgrading alternative (1), we evaluate the separate thickening of primary and secondary sludge: primary sludge is thickened by gravity while dynamic thickening is applied to secondary sludge. After thickening, mixed sludge goes to anaerobic digestion.

The dynamic thickening (i.e. in rotary drums) does not follow the principles of decantation by gravity, in this case, the sludge, is conditioned with a polymer solution producing large size flocs, which allows to achieve, by filtering the sludge over a cloth, very high flow rates and concentrations. The sludge concentration, resulting from the dynamic thickening depends on the polyelectrolyte dosing, the time of the sludge mixing with the polymer solution, the gradient of mixing velocity, and the specific hydraulic flow rate. The percentage of dry solids in the treated sludge is in the range of 5–7% (data from different suppliers). Considering the poor digestibility of the secondary sludge, we assumed the lower value of 5% for the thickened sludge.