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Research article

How far are we from closing the loop of sewage resource recovery? A real picture of municipal wastewater treatment plants in Italy

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ABSTRACT

This paper presents the results of a broad-scale survey of resource recovery implementation in Italian wastewater treatment plants (WWTPs). To the best of our knowledge, this is the first survey comprising a large number of WWTPs done in Europe: more than 600 plants were investigated, representing a treated load of around 20 million population equivalent (≈25% of the total in Italy). Conventional and innovative options for both material and energy recovery along the water and sludge line were surveyed, in order to i) offer a real and complete picture of the current state of resource recovery in WWTPs, and ii) underline key aspects and potential areas for improvements, as a baseline for future developments in the direction of more sustainable plants.

Survey outcomes showed that resource recovery is just in its infancy in sewage treatment: only 40% of plants perform at least one option for material/energy recovery. The action most often implemented is recovery of material from surplus sludge for agricultural purposes and the internal reuse of treated effluent as water for various types of plant maintenance. The production of energy from biogas also occurs frequently but only in large plants. On the other hand, some well-known options, such as external reuse of treated effluent or nutrients recovery, were implemented only in a minority of plants: this is likely due to limitations resulting either from strict regulation or difficulty placing recovered products on the market. In conclusion, an overall explanation of these driving forces within the system is explored.

1. Introduction

Urban wastewater treatment with secondary processes is now an extremely mature technology able to produce a safe effluent from the points of view of both human health and environmental impact (Batstone et al., 2015). However, the current demands from a rapidly growing human population and the consequent need for a more sustainable society are spurring new developments in sewage handling (van Loosdrecht and Brdjanovic, 2014). These developments have two main drivers: general process improvements/optimization, and treatment plants' contribution to the recycling of resources (Grant et al., 2012). Such goals can be achieved if all the resources available in wastewater are recovered, i.e., water itself, nutrients and energy, or in other words, as described by Verstraete et al. (2016), if a NEWEL nexus (Nutrients-Energy-Water-Environment-Land) is established. Sewage treatment can be designed with "flexible" technologies that theoretically allow for closing cycles and recovery of resources if plants are properly conceived. For this reason, the wastewater industry is facing a paradigm shift: wastewater treatment plants (WWTPs) are no longer designed merely as systems to remove pollution (end-of-pipe approach), but instead as factories where various value-added products can be recovered (resources-oriented approach). This means that, next to the production of a purified effluent, which remains an essential pillar of treatment, WWTPs can become (pro)active resource producers: from WWTP to WRRF (water resource recovery facility).

In the last few years, alternatives for resource recovery in WWTPs have been touted mainly for: (a) recovery of thermal, electrical and mechanical energy, to be consumed either inside or outside the

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plant, and (b) recovery of materials to be sold on the market. While renewable energy recovery (through biogas production and utilization, hydropower or heat from wastewater) is quite practicable, at least when energy is used immediately on-site in plant operations (also with the aim of a net energy balance: McCarty et al., 2011), conversely, recovery of materials presents some barriers due to their intrinsic properties: difficulties in handling and storage, contamination, constraints in commercialisation, and low public acceptance, because many residuals are still perceived as wastes (Verstraete et al., 2016). But even if the recovery and production of energy at sewage works is currently getting the most attention (also achieving energy self-sufficiency: see, for instance, Nowak et al., 2011), material recovery from wastewater and sludge (as phosphate and bioplastic production, etc.: see van Loosdrecht and Brdjanovic, 2014) should not be overlooked as they can play an important role in developing more sustainable services.

Therefore, assembling a detailed picture of the extent these actions are currently implemented in WWTPs is a fundamental starting point in boosting sustainability. However, this is difficult information to acquire, because comprehensive data about resource recovery applications in full-scale plants are rare on a broad scale (e.g., the national level) or incomplete in terms of surveyed options. For instance, surveys performed by NRC (2012) and WEF (2013) were restricted to effluent reuse and biogas production (and consequent energy recovery), respectively. Similarly, a broad survey covering the majority of European countries has been described by Kelessidis and Stasinakis (2012) but was limited to sludge reuse options. In summary, complete surveys of large geographical areas including all the potential options for energy and materials recovery at different stages of WWTP have not been investigated, so far.

In order to bridge this gap, we looked inside about 600 Italian WWTPs (corresponding to approximately a quarter of the national load of treated sewage). We showed the current status of implementation of resource recovery options: both conventional and emerging alternatives, for a total of 20 options corresponding to all phases of treatments in plants, were considered. Finally, we outlined the main driving forces playing a role in the implementation of recovery actions, either in favor or against: in this way, future efforts toward the development of more sustainable WWTPs could be easily identified.

2. Materials and methods

A 1-page, easy-to-fill-out questionnaire (Fig. 1) was elaborated for data collection; creating a clear, user-friendly form was essential to obtain a significant amount of responses: as a result, more than 600 WWTPs provided their data.

In brief, after a preliminary section related to general information on some of the main features of WWTP (such as plant configuration, treated load, etc.), the questionnaire lists a large variety of resource recovery options, both conventional and innovative. They were divided by type of resource (material *vs.* energy) and grouped by plant stage (water *vs.* sludge treatment lines): 20 options were considered, including the recovery of materials from screening, de-gritting and de-oiling; nutrients and biopolymers; treated effluent and sludge; heat and electricity from biogas; finally, the last section, called "Other Recovery Forms," accounts for recoveries taking place inside the WWTP but not involving wastewater directly (e.g., photovoltaic systems). They represent proper indicators of the current scenario, although the scientific literature is proposing some promising alternatives. For instance, the authors are currently carrying out a study aimed at recovering nutrients from sludge (Collivignarelli et al., 2015a) by running a thermophilic membrane reactor; this process has led to promising results indeed in liquid wastes treatment (Bertanza et al., 2010a; Collivignarelli et al., 2015b).

With respect to data processing, the survey outcomes were parameterized according to WWTP size; three classes were established: SMALL WWTPs, with a sewage treated load lower than 10,000 PE (Person Equivalent), MEDIUM (10,000 $\leq$ PE $\leq$ 100,000) and LARGE (PE > 100,000).

3. Results

3.1. Surveyed WWTPs

The questionnaire was very successful in eliciting feedback from plant managers. Twenty-nine water authorities provided their 2014 data, for a total of 627 WWTPs assayed. They correspond to around 5% of municipal WWTPs in Italy, approximately 16,000 in number (but this includes micro-plants with only primary treatment, e.g., Imhoff tanks). But, even more important, they represent a treated load of about 20 million PE, around 25% of the total load of municipal wastewater treated in Italy, according to the Italian National Institute of Statistics (ISTAT, 2011). This result was a fundamental achievement for this research, and ensures the statistical representativeness of our survey.

A wide range of WWTPs was included, varying from a minimum of 50 PE to a maximum of 4 million PE. Size distribution is presented in Table 1, showing how all the classes were represented, while the geographical distribution of surveyed plants in the Italian context (Northern, Central and Southern Italy) is reported in Fig. S1 of Supplementary Information.

3.2. Resource recovery implementation: a general overview

As a first and general outcome, the survey indicated that the level of implementation of resource recovery in Italian WWTPs is quite low. Indeed, fewer than half of surveyed plants (245 out of 627) perform as much as one type of resource recovery; the majority of Italian plants do not apply even one recovery option. Detailed information for each WWTP class is reported in Table 2: it demonstrates that recovery is performed mainly in large plants, with about 85% performing at least one action. This is an expected outcome, considering constraints in investments for small plants due to economies of scale.

The same data, presented in terms of treated load (data not shown) indicate a higher percentage of recovery (i.e., $\approx$75%, 15 out of 20 million PE), due to the predominance of large plants in the total treated load.

3.3. Resource recovery implementation: specific actions

This section analyzes the extent of diffusion of each recovery action. Percentage values are expressed in two ways:

i) first, out of all the surveyed plants (i.e., 627), in order to understand the overall extent to which each recovery option is practiced in Italy (Fig. 2A);
ii) then, a zoom-in was performed on the sub-group that implements at least one type of recovery option, in order to focus only on the "virtuous" plants: Fig. 2B reports such a ratio split up for plant size.

However, all the survey rough data are reported in Table S1 and S2 of Supplementary Material.

Overall, Fig. 2 clearly highlights how material recovery is definitely implemented more than energy recovery -with sludge reuse being the most common recovery action- and how a lot of options