An Innovative Technology to Minimize Biological Sludge Production and Improve Its Quality in a Circular Economy Perspective

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Abstract In the coming years, the production of biological sewage sludge is set to increase. According to the European legislation, the management of sludge, as well as other waste, must follow a hierarchical approach according to which the first place in order of priority is represented by the prevention/minimization of the production. Over the last few years, thermophilic aerobic processes proved to be effective in minimizing the production of sludge within wastewater treatment plants (WWTPs). Thermophilic aerobic/anoxic membrane reactor (TAMR) technology combines the advantages of thermophilic aerobic treatments with those of biological membrane processes. This work reviews the literature concerning the application of TAMR

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focusing on the prevention of the production of biological sludge and on the improvement of its quality for the purpose of a possible recovery in agriculture in a circular economy perspective. The results show that the process is mature and effective for full-scale application in conventional WWTPs.

Keywords Agricultural reuse, Aqueous waste, Circular economy, Sludge minimization, Thermophilic membrane reactor

1 Introduction

A growing production of biological sewage sludge (BSS) and a simultaneous worsening of the qualitative characteristics are the consequences of the imposition of more restrictive limits, as European Directive 91/271/EEC and subsequent amendments [1, 2], on the effluents of wastewater treatment plants (WWTPs) [3]. In 2015, European urban WWTPs produced 9.7 million tons of dry matter of BSS [4]. Therefore, a sustainable management of sludge is nowadays desirable and, above all, mandatory objective.

In fact, Directive 2018/851/EC [5] identified a hierarchy in waste management, therefore also applicable to BSS: (1) prevention and minimization of the production, (2) matter recovery and reuse, (3) energy recovery, and finally (4) safe disposal of waste. The prevention/minimization of the production of BSS at the source is an aspect of primary importance not only because the legislation requires it, but also because it can guarantee many non-negligible benefits including the reduction of costs incurred by WWTPs. As reported in literature [6–9], the management of sludge represents about 50% of the total operating costs of WWTPs. In addition to the economic aspect, the environmental impact linked to the treatments, transport and final disposal of the sludge must also be considered.

According to the Italian Higher Institute for Environmental Protection and Research, in 2017, Italian urban WWTPs produced about 3.2 million tons of sludge (about 0.8 million tons of dry matter) [10, 11], with 47.7% being sent for recovery and 50.6% for disposal, recording a 1.4% decrease in landfill disposal in favour of recovery compared to the previous year [10]. The European Directive 86/278/EEC [12] aimed at encouraging the use of good quality sludge in agriculture by banning the use of untreated sludge on agricultural land to avoid any harmful effects caused by the presence of pathogens and organic contaminants [13, 14]. The practice of reuse can be fully integrated into a circular economy vision [15, 16]. Concerning this aspect, in 2020 the European Commission adopted a new Action Plan for the Circular Economy to promote the sustainable use and reuse of resources [17]. In the urban water management system, one of the main actions needed to implement a circular economy approach is the transformation of WWTPs into water resource recovery plants (WRRFs) [18, 19]. To do this, the prevention and minimization of the production of BSS represents the first step that can be pursued in two distinct ways: (1) adopting processes capable of treating the water with a minimum production of residual sludge; (2) providing in situ treatments to minimize the quantities of sludge produced [4].

This chapter aims to provide an overview of the results obtained testing the thermophilic aerobic/anoxic membrane reactor (TAMR) technology which can guarantee both approaches described above.

2 The Technology

TAMR is an advanced biological process that simultaneously combines a pure oxygen membrane bioreactor (MBR) system and a thermophilic treatment in autothermal conditions. According to previous publications [20–24], the application of this combined process, in addition to having a low environmental impact as a biological technology, has the following advantages: (1) drastic reduction of the sludge produced, (2) high removal rates of slowly biodegradable compounds in mesophilic conditions, (3) excellent flexibility in case of organic overload, (4) high compactness of the system, (5) inhibition of pathogens, and (6) possibility of energy recovery.

The process can be applied both in the water line and in the sludge line of WWTPs. In case that aqueous waste is fed, TAMR operates only in aerobic conditions while BSS also require an anoxic phase to effectively minimize sludge production. Thermophilic conditions (47–53°C) are maintained thanks to the exothermic degradation processes of the thermophilic microorganisms. To ensure the self-heating of the process, the feed must be rich in organic matter and therefore, the water line application should be in WWTPs authorized for the treatment of aqueous waste, as an urban sewage would not guarantee the self-heating of the thermophilic process (Fig. 1). In the case of sludge line application, the TAMR can be used both to co-treat sewage sludge and aqueous waste and to treat only BSS from conventional active sludge (CAS) systems.

The TAMR produces (1) residual sludge (Sects. 3.1 and 3.2) and (2) aqueous permeate (Sect. 4). In Lombardy (Italy), there are currently two full-scale TAMR plants for the treatment of aqueous waste (sludge prevention through water line intervention).

3 Sludge Prevention/Minimization

3.1 Residual Sludge Production

Residual thermophilic sludge represents the excess sludge of the thermophilic biological system and can have a percentage of dry matter up to 19% [25–27]. Its production is lower in terms of mass and volume than that of the permeate. Table 1 shows the results of the specific production of thermophilic sludge obtained mainly

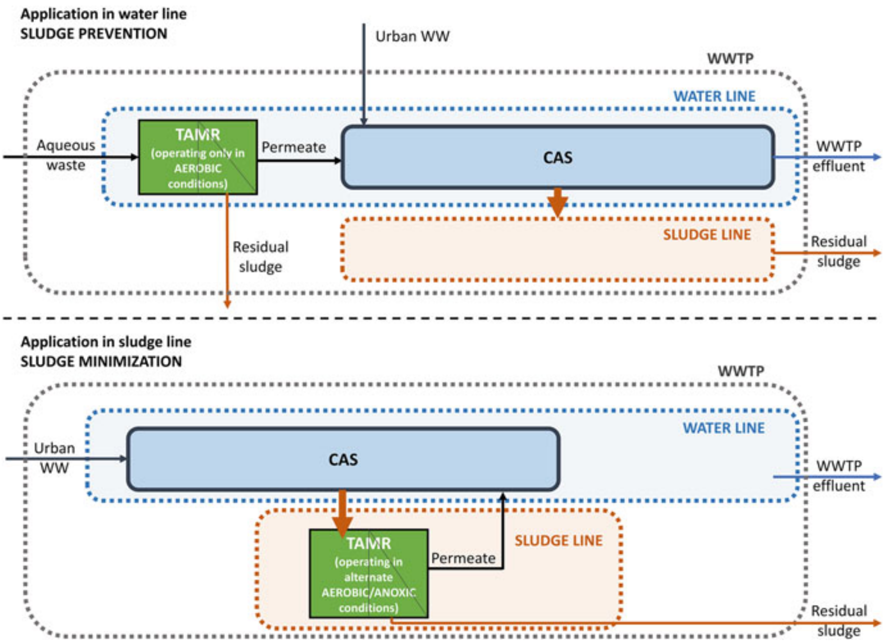

Fig. 1 Application of TAMR in water and sludge line. *CAS* conventional active sludge, *WW* wastewater

Table 1 Specific production of sludge in TAMR technology. *WW* wastewater, *R* real scale, *S* semi-industrial scale, *TP* total phosphorus, *TN* total nitrogen

Substrate	Scale	Specific sludge production $(kg_{VSS\ produced}\ kg_{COD\ removed}^{-1})$	References
Aqueous waste			
Pharmaceuticals and detergents production WW and landfill leachate	R	0.092–0.101	[26]
Saline WW, neutral/acid/basic WW, landfill leachate, solvent WW, and slurries	R	0.08–0.09	[25]
WWs with highly recalcitrant pollutants (e.g., surfactants, solvents, pharmaceutical products)	R	0.052[a]	[27]
High strength WWs	S	0.09	[28]
High strength WW mainly containing dyes, surfactants, and solvents	S	0.04	[20]
WW with high concentrations of COD, TP, TN, chloride, acetic acid, methylene chloride, ethanol	S	0.016	[29]
Aqueous waste and sewage sludge[a]	S	0.04	[30]

[a] Expressed in $kg_{VS\ produced}\ kg_{COD\ removed}^{-1}$

[b] Mixture composed of 30% sewage sludge and of 70% of aqueous waste

during experiments at the semi-industrial scale of the TAMR technology both on diverse aqueous waste and on BSS. In the case of aqueous waste treatment, specific sludge production data monitored in full-scale plants are also available. These results are lower than those achievable with a mesophilic MBR (0.10–0.19 $kg_{VSS\ produced}\ kg_{COD\ removed}{}^{-1}$) [21, 31] and close to those reported in the literature for aerobic thermophilic processes (0.08 $kg_{VSS\ produced}\ kg_{COD\ removed}{}^{-1}$) [21], (VSS: volatile suspended solids; COD: chemical oxigen demand). Even the granular anaerobic processes have higher values than the TAMR technology: for example, the specific production of sludge in a UASB reactor that treats sewage sludge is equal to 0.1 $kg_{VSS\ produced}\ kg_{COD\ removed}{}^{-1}$ [32].

3.2 Sludge Quality Improvement

In general, the Italian legislation on the recovery of sludge in agriculture imposes some stricter limit values (such as on total chromium, lead, arsenic, agronomic parameters, and several organic contaminants) compared to other legislations, including the French and German ones. In particular, in the current legislation in Lombardy (Italy) [33], a distinction is required between "suitable sludge" and "high quality sludge". Sludge suitable for spreading in agricultural fields must comply with the limit values set by current Italian legislation, while "high-quality" sludge requires more stringent limit values than national ones.

Regarding the thermophilic sludge residue, the only criticality could be represented by the insufficiency of organic carbon, which can be solved by mixing other BSS with the thermophilic sludge normally with high concentrations of COD [30].

However, in an experiment involving the treatment of industrial wastewater with high concentrations of chlorides and perfluoroalkyl, although most of the COD introduced was oxidized in the TAMR, only a minor but still significant part (6–12%) remained in the thermophilic sludge [34].

A high concentration of phosphorus in the crystalline phase has been identified in the thermophilic sludge. In the thermophilic reactor, the chemical precipitation of total phosphorus takes place in the form of salts, such as vivianite and hydroxyapatite [28, 29]. In agreement with the scientific literature [35], these results could be related to the increase in pH induced by the aeration of the reactor which allowed the crystallization of phosphorus [28].

A significant amount of nitrogen in the thermophilic sludge was also observed due to (1) the absorption of nitrogen by the biomass, (2) adhesion to sludge, and (3) precipitation of ammoniacal nitrogen in the form of struvite [29, 34].

As regards the presence of pathogenic microorganisms, thermophilic processes generally guarantee greater safety than the mesophilic ones, thanks to higher process temperatures [23, 24]. Therefore, thermophilic extracted sludge could be suitable for spreading in agriculture thanks to the high content of carbon, nitrogen, phosphorus, and potassium, the excellent degree of humification and sanitation that guarantees a

Table 2 Qualitative characteristics of mixed liquor. *TN* total nitrogen, *TP* total phosphorus

Results on nutrients	References
Organic carbon accumulation (6–12% of COD fed)	[8, 30, 34]
Nitrogen presence (8–10% of VSS; 8–24% of TN fed)	[26, 29, 30, 34]
Accumulation by chemical precipitation of phosphorus as inorganic salts (70–80% of TP fed)	[28, 29, 34, 36]
Other results	
High concentration of total solids (up to 190 kg m^{-3} in the full-scale applications)	[25–27]
Absence of foaming phenomena during the treatment of liquid waste (real laundry wastewater rich in TAS e MBAS)	[37]
Sanitation thanks to high temperatures (>45°C)	[26, 29]

healthy and safe recovery of the sludge. Table 2 shows the main qualitative characteristics of the thermophilic sludge extracted from TAMR.

4 Possibility of Permeate Reuse

Among the residues, the permeate is the most significant from a quantitative point of view. The ultrafiltration membranes allow to keep all the biomass inside the biological reactor, obtaining a permeate totally solids-free substrate [8]. In addition, it is rich in ammoniacal nitrogen thanks to excellent ammonification activity by the thermophilic bacteria in TAMR [30, 38]. Despite the excellent performance of TAMR process (COD removals up to 90% [26, 29, 30]), permeate contains significant concentrations of well biodegradable COD by a mesophilic biomass, confirming the complementarity between mesophilic and thermophilic processes for the biodegradation of organic substances [20, 26, 28, 36].

Therefore, this substrate can first be subjected to a stripping treatment for the recovery of ammonia nitrogen in the form of ammonium sulphate and, considering the good biodegradability of the organic substance by mesophilic biomass, recirculated in the denitrification reactor of a CAS to improve the kinetics of nitrate removal, in place of external sources of carbon of synthetic origin [27, 29, 34, 38].

5 Tips for Future Research and Applications

Considering the depletion of world natural reserves of phosphorus, it would be interesting to investigate the bioavailability of this nutrient in the sludge extracted from TAMR to evaluate the direct assimilation by crops in case of agricultural reuse.

Another aspect that would be interesting to investigate is the application of the technology on BSS resulting from the treatment of industrial wastewater and aqueous waste. In this case, the authors suggest evaluating the performance of

TAMR to minimize BSS production considering feed with diverse characteristics and comparing the results with those obtained treating urban BSS. At the same time, examining a possible toxic and chronic effect of these substrates on the thermophilic sludge can represent an interesting point that should be further investigated.

The authors also suggest studying the up-grade of the process. For instance, the introduction into the reactor of a mobile support material for the development of attached biomass could be an aspect to be investigated. The traditional suspended biomass already present and the new adherent biomass developed on supports with a high specific surface would thus work simultaneously, guaranteeing a hybrid process. The support materials introduced into the thermophilic reactor could also be recovered through recycling operations according to a circular economy perspective applied to integrated urban water cycle.

6 Conclusions

The TAMR technology ensures the prevention/minimization of the production of BSS and guarantees the recovery of the residues produced. The excess sludge extracted from the thermophilic biological reactor could be destined for recovery in agriculture thanks to its content of nutrients (organic carbon, nitrogen, and phosphorus) and greater protection against the pathogenic load. At the same time, the permeate can be reused as an external carbon source in a post-denitrification process, after stripping to produce ammonium sulphate, thanks to the high content of ammonia nitrogen and well-biodegradable organic carbon by mesophilic biomass. In this way, both residues obtained from the TAMR acquire an economic value as products, guaranteeing the important possibility of closing the cycle linked to the management of wastewater and BSS in a circular economy perspective.

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