Waste-Water-Energy nexus: a feasible, sustainable approach in climate-change affected Mediterranean regions

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The potential for setting up new Industrial Symbiosis synergies in waste/wastewater management is often limited by a variety of non-technical barriers. These barriers include environmental regulations, a lack of cooperation and trust among industrial systems, economic and legislative barriers, and last but not least, a lack of information on the possible benefits that can be achieved. Many Mediterranean regions continue to have disjointed and unsustainable approaches to the management of waste, wastewater, and residual biomass, which influence their energy consumption and still have serious impacts on the environment. Many of these regions also suffer from severe water shortages, a condition that is continually aggravated by climate change. Therefore, the availability of marginal water resources should be considered crucial to meet the future demand for water for agriculture. But the high costs of wastewater treatment to obtain the (excessive) quality of the water required for reuse in agriculture still makes the cost of this unconventional resource absolutely out of the market compared to traditional water resources [8]. Added to this is a widespread condition that sees, in these regions, many wastewater treatment plants suffer from serious problems related to the treatment and disposal of the sludge produced, with landfills often reluctant to accept sludge that has not been adequately stabilized and dehydrated. Condition to which it overlaps and will increasingly overlap the drastic reduction of the possibilities of direct or indirect use (through composting) of sludge in agriculture due to the potentially harmful effects on the soil and on the food chain. In many of the large metropolitan areas of southern Italy - but also southern Europe - it is still possible to promote a new eco-systemic model of integrated management that can drastically increase the overall circularity and sustainability in these areas through the exploitation of the "waste-wastewater-energy nexus".

The purpose of this work is to propose a new model of industrial symbiosis (IS) that can close the loop between waste, wastewater, and energy from a sustainable point of view. Starting from the current scenario, the future management of waste, wastewater, and the associated energy recovery systems is devised from the perspective of IS with the aim of shifting from the current linear economy in waste and wastewater management to a circular economy through a holistic approach. Through it, large savings should be obtained in terms of new resources and energy, as well as a significant reduction in greenhouse gas (GHG) emissions and toxic substances. The investigated model aims at integrating: 1) the existing wastewater treatment plant, 2) an enhanced anaerobic digestion plant for the contextual (not necessarily joint) treatment of OFMSW and sludge, and 3) a new WtE with the production of electricity and heat to recover the energy value of the residual waste and scraps from the selection. The symbiotic exchanges between the three systems, which have been deeply analysed through mass and energy balances (Mancini *et al*. 2021), if well designed are relevant and allow a formidable energy optimization while maximizing the material recovery. The proposed integrated model (Figure 1) provides numerous advantages:

1) The energy content of the OFMSW is recovered, leaving only the residual maturation phase to the most expensive composting with an advantage in terms of direct and indirect CO_2 emissions (saving electricity in the aerobic phase) in the production of quality compost.

2) Part of the heat generated by the WtE process - appropriately commensurate, through a well-dimensioned management of steam tapping - can also be used in hot climates to conduct digestion in the thermophilic phase and therefore reduce digestion times and volumes by increasing the biogas production yield with an advantage that affects also higher efficiency in the digestion of sludge compared to more traditional mesophilic processes.

3) The biogas thus produced can be totally converted into biomethane (instead of partially using it in cogeneration systems to heat the digester) thus maximizing any incentives.

4) Part of the heat from the WtE plant can be used in the process of converting biogas into biomethane, reducing its production costs. Its increased use in public transport can further reduce GHG emissions.

5) The supernatant of both OFMSW and sludge digestion can be used to recover phosphorus (struvite) and polyhydroxyalkanoates (PHA).

6) Part of the heat from the WtE plant can be used to pre-dry the mechanically dehydrated sewage sludge with a view to its energy recovery, possibly in a dedicated line of the WtE plant itself, which can also collects contributions from other smaller nearby plants, to ensure recovery of phosphorus from the ashes and eliminate the problem of sludge final disposal.
7) Part of the heat from the WtE plant can be used to pre-dry additional biomass from the agricultural sector before its energy recovery in the same WtE plant, again reducing disposal problems;
8) Part of the heat from the WtE plant can be used to support any companies (existing or wishing to enter the industrial district) by exploiting the residual heat at advantageous conditions for their processes (e.g. agri-food process industry), in addition to any heating and cooling needs, in a full perspective of industrial symbiosis and with a consequent reduction in CO_2 emissions.
9) The electricity produced can be partially used (a few percentage units) to support the tertiary treatment and pumping phase of the treated wastewater to agricultural areas in order to make the cost of treated wastewater competitive to conventional resources, guaranteeing its reuse from a perspective market and thus avoiding that the concentrated load is discharged into water bodies with the related impacts, especially in islands and coastal areas.
11) An additional part of the electricity produced by the plant could be used to support the entire wastewater treatment process with a view to industrial symbiosis. The oxidation phase in the water line should in any case be carried out as a classic high-load scheme to minimize energy consumption, taking into account the subsequent reuse also through containment of nitrification. The efficiency on the abatement of the organic fraction could be better achieved through tertiary systems with self-cleaning filters (coupled to UV for disinfection) which have low energy costs and excellent efficiencies. It is essential to couple an appropriately sized and managed water storage system that, in addition to ensuring a better final quality of the final irrigation effluent [19, 20], allows its full use throughout the year and not only in the irrigation season, avoiding it continuous discharge so achieving the "ZERO discharge plant" condition.
12) The residual fraction and non-recyclable waste are reduced in volume (about 10%) by reducing the need for landfills and the consequent impacts.
13) The reduction of waste to be disposed of in landfills could be further limited to inertized fly ash only (about 2% of the total waste, in full compliance with the European directives that set the limit of 10% for 2035) thanks to bottom ash recovery processes, increasingly consolidated, which could allow increasing the overall recovery of material (additional 10-15% of the gross waste production) - through certified products – so to considerably increase the circularity of the entire system.
14) A part of the CO_2 produced by the conversion process into biomethane and/or contained in the fumes of the WtE plant could be converted into algal biomass to be used for products with high added value and/or for energy conversion through the same anaerobic digestion.

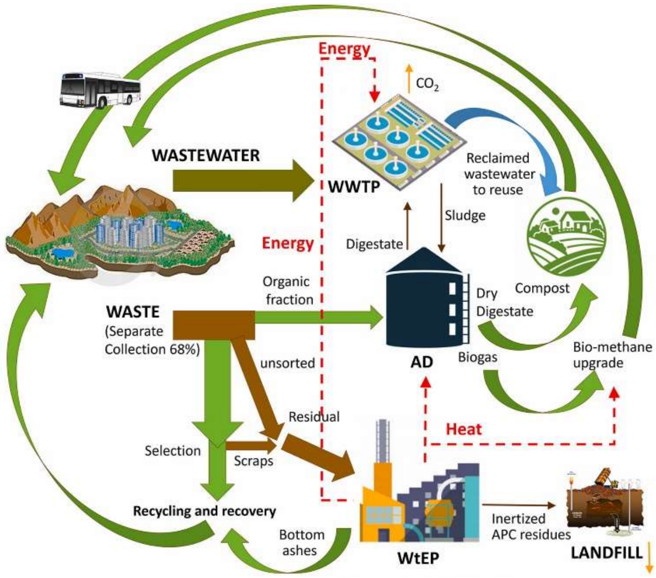

Figure 1: The Waste-Wastewater-Energy Nexus concept through Industrial Symbiosis.

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