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The grand challenge of water, waste, wastewater and emissions engineering and valorization

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Introduction

Water, soil, and air represent the three main environmental ecosystems and natural resources of our planet. They have faced increased environmental concern, mainly over the last century and since the era of industrialization and heavy industrial development, which resulted in significant pollution issues never faced before. On the other hand, wastewater, solid waste, and air/gas emissions are seen as the most important sources of pollution on earth, besides noise, light, and thermal pollution which have more recently been identified to be of environmental concern and affect human health and welfare as well. The current situation of water, waste, wastewater related issues, as well as gas emissions from those sources are briefly addressed hereafter as well as their treatment and valorization alternatives.

Current situation

Water, wastewater

As much as somewhat more than two-third of our planet is covered by water, while only 3% of the earth's water is fresh and hardly about 0.5% is easily accessible for use (e.g., lakes, rivers, and aquifers); the remaining fraction being unavailable for direct use (e.g., glaciers, polluted water). The largest fresh water application is presently for irrigation and agriculture, though many countries suffer from water scarcity. A recent study revealed that by 2050, as much as 87 out of 180 countries will have annual renewable water resources (ARWR) *per capita* below 1700 m^3/year, i.e., they will face water scarcity concerns; while the number of countries with ARWR *per capita* below 500 m^3/year, this is absolute water scarcity, is expected to increase from 25 in 2015 to 45 by 2050 (Baggio et al., 2021).

On the other side, globally, 380 billion m^3 of municipal wastewater are generated yearly and this value is expected to increase further, by about 51% by 2050 (Qadir et al., 2020). A large amount of those wastewaters is still released, untreated, into the environment. Information reported only a few years ago suggested that high-income countries treat about 70% of their wastewaters, while this drops to 38% in upper-middle-income countries, 28% in lower-middle-income countries, and hardly 8% in low-income countries (Sato et al., 2013).

Waste

Besides (waste) water, solid waste is another source of pollutants, mainly generated in the form of municipal waste, industrial waste, and it may also come from agriculture and food, among others. It is mainly composed of organic compounds as well as non-organic ones such as plastics, glass, metals, or paper. Waste treatment, e.g., in landfills, may additionally result in groundwater contamination from landfill leachates. According to Eurostat data (https://ec.europa.eu/eurostat/, accessed 09-01-2023), 4.8 tonnes of waste were generated per EU citizen in 2020, of which 59.1% was treated in recovery operations, i.e., recycling, backfilling or energy recovery; the remaining fraction being mainly landfilled, or, otherwise, to a lower extent, incinerated without energy recovery or disposed of. The amounts generated per EU member states are highly variable, and range from less than 1.5 tonnes per inhabitant in Portugal to, as much as, 21 tonnes per inhabitant in Finland. In terms of sources and polluting sectors, the industrial sector generates the highest amounts of waste, mainly through activities such as construction and manufacturing. On the other side, municipal waste accounts for about 10% of total wastes produced, which means that around 530 kg waste *per capita* were generated in the EU in 2021. In terms of treatment alternatives, those wastes are mainly landfilled, incinerated, recycled or composted, but, following EU regulations, the main goal of most countries, regarding wastes, is to minimize their accumulation and, as far as possible, maximize recycling, reuse, and valorization.

Air emissions

Next to water pollutants and solid waste, air pollution is one of the most significant health and environmental problems. Air pollution is also related to water pollution and solid waste, as the latter and their treatment plants do often generate emissions of volatile pollutants. These may be greenhouse gases (GHG), such as methane (CH_4), or carbon dioxide (CO_2), but also nitorgen oxides (NO_x), as well as other toxic inorganic and organic volatile compounds (Kennes and Veiga, 2013). According to the World Health Organization (WHO), it is estimated that air pollution kills around seven million people worldwide every year, and almost the entire global population breathes air that exceeds WHO air quality limits (https://www.who.int/news/accessed 09-01-2023). As briefly illustrated hereafter, diverse pollutants are emitted from wastewaters, solid wastes and their treatments plants.

Wastewater treatment processes emit some GHG, i.e., CO_2, CH_4, N_2O, during their biological treatment, while indirect emissions result from off-site power generation mainly and contribute to significant amounts of CO_2. Ammonia can also be released from wastewaters containing nitrogen, though these emissions can be reduced by replacing conventional nitrification-denitrification processes by Anammox processes. N_2O emissions can result from nitrification-denitrification of nitrogen compounds as well. Besides, methane is mainly released during the anaerobic decomposition of organic matter, in the secondary anaerobic treatment process, in the sewer system or in the sludge line. This may also lead to emissions of odorous compounds such as hydrogen sulphide (H_2S). Next to GHG, some volatile organic compounds (VOC) have also been detected at wastewater treatment plants and often result from stripping and volatilization phenomena, e.g., in aerobic activated sludge aeration tanks (Hamoda, 2006). They me be aliphatic or aromatic and their nature and concentrations depend largely on the origin and composition of the wastewater.

In case of solid waste, gas emissions depend on the treatment process applied. In the European Union (27 countries, EU-27), according to 2020-statistics, the energy sector and the combustion of fuels are, by far, still the most significant contributors to greenhouse gas emissions (75%), followed by agriculture (11.5%) and industrial processes and product use (9.5%), and then waste (3.5%) (https://stats.oecd.org/accessed 09-01-2023). Contrary to other types of plants and processes, municipal solid waste landfills are among the major sources of the greenhouse gas methane. Although waste decomposition in landfills is initially aerobic, after several month, conditions become anaerobic and anaerobic methanogens start producing methane and carbon dioxide.

A recent report indicated that landfilling emits nearly 400 kg CO_{2e} per tonne of organic waste, while composting raw organics results in the lowest GHG emissions, at −41 kg CO_{2e} per tonne of waste, and upgrading biogas to renewable natural gas after dry anaerobic digestion results in −36 to −2 kg CO_{2e} per tonne (Nordahl et al., 2020). According to estimates of the European Environmental Agency, greenhouse gas emissions from waste, in the EU-27, have decreased by about 32% between 2000 and 2020 (https://stats.oecd.org/ accessed 09-01-2023). This is due among others to higher levels of waste recycling and composting, concomittant with less waste being disposed in landfills. Odours, ammonia, sulphur oxides (SO_x), as well as some volatile organic compounds (VOC) have also been detected at landifills and waste treatment sites (Fang et al., 2012). In case of waste landfill sites, a recent study undertaken in China reported the presence of mixtures of VOC at concentrations ranging from 18.1 to 806.3 mg/m^3, while odorous gases and greenhouse gases ranged from 0.4 to 21.2 and 0 to 100.5 mg/m^3, respectively (Wang et al., 2021).

Current treatment and valorization trends

Water, wastewater, and waste tretament technologies have been developed, optimized and applied for many decades, as well as techniques for the treatment of air and gas emissions from such sources, using either biological or non-biological processes, which have been described in scientific literature (Kennes et al., 2009; Metcalf and Eddy et al., 2013; Pichtel, 2013). However, recent trends and approaches are more focussed on the valorization of pollutants, their reuse, and resource recovery from polluting sources. The latter are then considered as valuable resources rather than pollutants to be eliminated and they may even generate benefit instead of resulting in mere treatment and elimination costs. Although a comprehensive overview of all possible and numerous valorization alternatives for (waste) water, waste and their gas emissions is beyond the scope of this brief overview, some basic aspects will be explained herefater.

Water, wastewater

Different methods and different valuable products can be produced or recovered from wastewaters (Puyol et al., 2017). In terms of resource recovery, it is estimated that, on an average, wastewaters contain 16.6 million metric tonnes (Tg) of nitrogen embedded in wastewater produced worldwide annually, while phosphorus stands at 3.0 Tg and potassium at 6.3 Tg. These can be recovered, while simultaneously reducing eutrophication problems

(Qadir et al., 2020). This solves also the problem of possible, near future, progressive shortage of phosphorus, largely obtained from non-renewable mineral resources. Besides, it is considered that energy embedded in municipal wastewater corresponds to the same amount of electricity used in 158 million homes. Energy that can be recovered from municipal wastewater is basically thermal energy (about 80% of energy recovered) and, to a lower extent, chemical energy (20%), and finally, a smaller amount of hydraulic energy. Additionally, the organic compounds present in wastewater can also be converted into methane-rich biogas and although methane is a GHG, if it is recovered, it can be used as a valuable energy source. Wastewater pollutants, mainly the organic fraction, can even be (bio) converted to other biofuels or energy carriers, such as biodiesel or hydrogen (Puyol et al., 2017). It is worth further highlighting that, besides energy sources, wastewater pollutants can be (bio) converted to bioproducts, which can be simple compounds such as short chain and medium chain carboxylic acids (e.g., acetate, propionate, butyrate, valerate, caproate) (Mato et al., 2010), but also higher value commercial compounds such as biopolymers (i.e., bioplastics) (Ben et al., 2016) or single cell proteins (Shoener et al., 2014), to mention only few examples. Finally (waste) water is also an important resource in itself as it can be treated and reused either as potable (i.e., drinking water) or non-potable (e.g., for irrigation, industrial use) water.

Waste

Waste is another potential valuable resource. Part of the non-organic fraction of waste can be recycled, while the organic fraction can decompose and release gases such as methane and carbon dioxide, which can be emitted as GHG involved in climate change. However, in a similar way as with wastewater, that organic fraction can also be valorized and recovered in the form of biogas (methane), used as a biofuel (Eiroa et al., 2012). Composting and vermicomposting are other viable options to valorize organic waste. In vermicomposting, microorganisms and worms convert organic waste into nutrient-rich humus and fertilizers with applications in agriculture (Mupambwa and Mnkeni, 2018). Still more recently, black soldier flies have been shown to grow on organic waste and use their nutrients. They are a potential source of proteins, organic fertlizers and can also generate other bioproducts (Xiao et al., 2018). Again, similarly as for wastewaters, organic waste can be bioconverted to short chain volatile fatty acids (e.g., acetate) or medium chain carboxylic acids (e.g., caproate) (Bermúdez-Penabad et al., 2017). Actually, some of the metabolites obtained from either wastewater or solid waste, such as those fatty acids, can then still further be (bio) converted, in a second stage, into other more or highly valuable end products, e.g., microbial oils or other metabolites accumulated by yeasts (Robles-Iglesias et al., 2023). Studies have also been performed on the direct production of other biofuels, e.g., waste bioconversion to bioethanol (Bibra et al., 2023) or thermochemical waste conversion processes for energy recovery (Kassim et al., 2022). Numerous other non-energy-related bioproducts have been obtained from organic waste as well, e.g., antioxidants (Kaur et al., 2019), lactic acid (Wang et al., 2016), citric acid (Yu et al., 2017), to mention only few.

Air emissions

The valorization of gas emissions from wastewaters and wastes as well as their treatment plants has hardly been studied and research in this field is still rather recent. The most studied gases are methane and carbon dioxide, released, for example, from anaerobic digestion in the water and waste sectors, while aerobic wastewater treatment has also been identified as a main source of CO_2 (Bajón-Fernández et al., 2017). Quite more research has been performed on the valorization of gas emissions, e.g., CO, CO_2, in other industrial sectors such as steel industry emissions, allowing to produce numerous compounds from such gases, such as fatty acids (Ragsdale and Pierce, 2008), bioalcohols (ethanol, butanol, hexanol) (Fernández-Naveira et al., 2017), or numerous other bioproducts (Köpke and Simpson, 2020), which demonstrates the potential of gas valorization in the industrial sector but also many other ones, such as the (waste) water and waste sectors. Besides carbon dioxide, different (thermo) chemical (Ahmad et al., 2022), and biological (Jawaharraj et al., 2020) conversion processes are also available for CH_4 valorization.

There is thus room for much interesting additional research on water, wastewater, and waste engineering and on the valorization of those sources as well as their emissions. Many interesting research data and scientific information are expected to appear in the literature, in the short term, in this fascinating field based on environmentally-friendly and sustainable circular bioeconomy approaches.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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