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1

Wastewater treatment development

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1.1 INTRODUCTION

Chapter 1 on Wastewater Treatment Development in the book *Biological Wastewater Treatment: Principles, Modelling and Design* (Chen *et al*., 2020) (referred to hereafter as the textbook) explains how current wastewater treatment technologies have evolved over time. It describes the main drivers for sanitation on the historical journey from ancient cultures, passing through the Middle Ages and into the 20th century, thus providing deeper insight into the wastewater treatment technologies that have been developed. This chapter aims to guide readers through the contents of Chapter 1 in the main textbook in order to emphasize the factors that have driven and supported the development of the wastewater treatment technologies available up to now, and also to increase their understanding of how and why new technologies and applications will be developed in the near future.

1.2 LEARNING OBJECTIVES

After the successful completion of this chapter, the reader will be able to:

1. Describe the main purposes and drivers of sanitation and wastewater treatment technologies.
2. Discuss the development of sewage collection and wastewater treatment systems.
3. Define the main characteristics and advantages and disadvantages of existing wastewater treatment technologies.
4. Explain the main factors that have supported and led to the development of nutrient removal systems, instrumentation, control and automation, disinfection and micropollutant removal.
5. Distinguish different resources that have been or could be recovered from wastewater.

1.3 EXERCISES

Exercise 1.3.1
What are the main global drivers for sanitation?

Exercise 1.3.2
Describe ancient practices or applications used to recover resources from wastewater.

Exercise 1.3.3
What were the sanitation conditions in the Sanitary Dark Ages?

Exercise 1.3.4
In the Modern Era, when were the first sanitary collection systems installed or put into practice?

Exercise 1.3.5
What was the first water-free vacuum collection system implemented?

Exercise 1.3.6
What were the first biological wastewater treatment systems?

Exercise 1.3.7
Why were activated sludge systems named this way?

Exercise 1.3.8
Why is the Biochemical Oxygen Demand (BOD) determined over a duration of 5 days?

Exercise 1.3.9
What was one of the first applications of mathematical modelling in the wastewater treatment field?

Exercise 1.3.10
What led to the introduction of nitrification in wastewater treatment systems?

Exercise 1.3.11
What were the first treatment systems used to perform nitrification?

Exercise 1.3.12
Describe the main disadvantage of the first wastewater treatment systems applied to perform nitrification.

Exercise 1.3.13
What is eutrophication and why is it an undesirable process in receiving waters?

Exercise 1.3.14
What was and continues to be one of the main applications of the Monod kinetic expression?

Exercise 1.3.15
What supported the development of the nitrification-denitrification processes?

Exercise 1.3.16
What led to the development of the pre-denitrification systems?

Exercise 1.3.17
What was the first activated sludge configuration to combine the pre-denitrification and post-denitrification processes?

Exercise 1.3.18
Describe the main characteristics of the Pasveer ditch system developed in 1959.

Exercise 1.3.19
Why is it important to also remove phosphorus in order to prevent eutrophication?

Exercise 1.3.20
Explain why it is assumed that the Enhanced Biological Phosphorus Removal (EBPR) process was discovered by accident.

Exercise 1.3.21
What is the main characteristic of the Phoredox system developed by Barnard in 1976?

Exercise 1.3.22
What led to the development of anaerobic wastewater treatment technologies?

Exercise 1.3.23
Describe the factors leading to the development of the latest biofilm-based treatment systems.

Exercise 1.3.24
How is the solid-liquid separation process carried out in a membrane bioreactor (MBR) system?

Exercise 1.3.25
What is the Nereda® process and what removal processes does it perform?

Exercise 1.3.26
What was the reason to upgrade existing wastewater treatment plants by carrying out the removal of nutrients in the sludge treatment line?

Exercise 1.3.27
List at least five resources that can be recovered or generated from wastewater.

Exercise 1.3.28
What is the main advantage of the development and implementation of instrumentation, control and automation (ICA)?

Exercise 1.3.29
Why have disinfection and the removal of micropollutants of emerging concern received an increasing amount of interest in recent decades?

Exercise 1.3.30
Describe the main driver behind the use of seawater for toilet flushing and the advantages of this practice.

ANNEX 1: SOLUTIONS

Solution 1.3.1

Mainly, good public health by minimising waterborne diseases. In addition, together with access to safe water, it is essential to eradicate poverty, building liveable and prosperous societies.

Solution 1.3.2

In China from around 200 BC and up to the 1970s, due to recognition of its fertilizing value, the vast majority of agricultural land was fertilized by human faeces from latrines. In the Indus valley, in the Euphrates region and Greece, sewage and stormwater were being collected in basins outside the cities and used for irrigation purposes and to fertilise crops and orchards from before 2000 BC.

Solution 1.3.3

In the Sanitary Dark Ages, sanitation conditions were rather precarious: waste was simply disposed of in the streets, often by emptying buckets from second-storey windows.

Solution 1.3.4

In the Modern Era, the first sanitary collection systems were put into practice in several cities, driven by the city dwellers who no longer wanted to put up with the stench. Carts drove through the streets to empty buckets that were full of waste. Farmers located around the cities made use of this practice because they used the 'humanure' to fertilise. However, spillages during transportation and emptying did not help to reduce the smell.

Solution 1.3.5

The Liernur pneumatic sewer system was developed by Mr. Liernur in around 1900. The system collected toilet water using a vacuum sewer.

Solution 1.3.6

Biological filters were the first biological treatment systems to treat the sewage from towns and cities, mostly in the United States and United Kingdom, and they were introduced between 1893 and 1901.

Solution 1.3.7

Based on fill-and-draw wastewater treatment experiments by Ardern and Locket (1914), a highly treated wastewater effluent was produced resembling a sludge. Believing that the working principle was similar to activated carbon, the sludge was therefore called activated sludge.

Solution 1.3.8

In the first half of the 20th century, the river into which the (treated) wastewater was discharged was considered an integral part of the treatment process. Since the longest time that water spent in the rivers of the UK before it reached the sea is 5 days, this was chosen as the duration of the BOD test.

Solution 1.3.9

A mathematical model presented by Phelps (1944) in the book *Stream Sanitation*. It was applied to calculate the maximum organic load to a river from the oxygen sag curve. This was to prevent the dissolved oxygen (DO) concentration falling below a minimum value at a defined point downstream the wastewater discharge point.

Solution 1.3.10

To decrease the oxygen demand in rivers and the toxic effect that ammonia has on aquatic species.

Solution 1.3.11

Low-loaded trickling filters plants in the USA, Europe and South Africa.

Solution 1.3.12

The low-loaded trickling filters failed to nitrify consistently throughout the year, in particular due to the lower temperatures experienced in winter.

Solution 1.3.13

Eutrophication is the excessive growth of algae and other plants in surface water bodies due to the fertilizing effect of nitrogen (N) and phosphorus (P). It is an undesirable process: during the day there is a large photosynthetic production, and during the night oxygen depletion occurs and therefore plants and fish die off. The decaying biomass contributes even more to oxygen shortage. In addition, cyanobacteria (which also proliferate during the eutrophication processes) generate toxins that have a major deleterious effect on aquatic organisms and this affects the use of the water body as a source of (potable) water. Consequently, eutrophication may decrease water availability, affecting key sectors and activities (such as food production, industry and even tourism and recreation).

Solution 1.3.14

Its application to describe the growth rate of bacteria as a function of the substrate concentration. In particular, in 1964, Downing *et al.* used it to show that the nitrification process depends on the maximum specific growth rate of autotrophic organisms (Downing *et al*., 1964). This demonstrated that their growth is slower than that of ordinary heterotrophic organisms and that biological wastewater treatment systems had to be designed and operated at sludge ages long enough to enable the growth of autotrophic organisms to achieve consistently low effluent ammonia concentrations.

Solution 1.3.15

The advanced studies on bioenergetics carried out by McCarthy (McCarthy, 1964). He showed that nitrate generated by the nitrification process could be used as an alternative for oxygen by certain heterotrophic organisms and it is thereby converted to dinitrogen gas. Unaerated sections were included in activated sludge systems to induce denitrification, thus saving aeration energy and removing nitrogen.

Solution 1.3.16

Ludzack and Ettinger (1962) proposed an unaerated stage prior to the aerated stage in order to increase the denitrification rate by utilizing the organics present in wastewater (see Figure 5.13B in Chen *et al.,* 2020). This configuration was preferred to the post-denitrification system proposed by Wuhrmann (1964) which had an unaerated section after the aerobic nitrification stage and used methanol as its external carbon source to increase the denitrification rate. Due to the methanol addition, the post-denitrification configuration had higher operational costs and it was contradictory to add organics to the unaerated stage after the ones present in the influent wastewater had been removed in the aerated section. Thus, pre-denitrification configurations became more popular than post-denitrification ones. However, systems with post-denitrification stages are able to achieve lower effluent total nitrogen concentrations (e.g. lower than 5 mgN/l) if required (Chen *et al.,* 2020).

Solution 1.3.17

The 4-stage Bardenpho system (Barnard, 1973). This system, developed in South Africa by James Barnard in 1972, combined the pre- and post-denitrification reactors and introduced recycle flows to control the nitrate entering the pre-denitrification unit (see Figure 5.13C in Chen *et al.,* 2020).

Solution 1.3.18

This was a simple and economical system solely composed of one treatment tank with no primary settler or secondary settling tank. It followed the fill-and-draw principle developed by Ardern and Locket in the UK in 1914 (Pasveer, 1959). Moreover, if operated with continuous feeding, it was able to achieve simultaneous nitrification and denitrification. These continuously operated oxidation ditch and carrousel systems evolved from the Pasveer system but included a secondary settling tank.

Solution 1.3.19

Because phosphorus has been identified as the main enabling element for eutrophication in several ecosystems, removing only nitrogen is therefore insufficient to prevent it. Microorganisms (especially blue-green algae) can use nitrogen gas as a nitrogen source, and therefore phosphorus is the main growth-limiting compound in surface water.

Solution 1.3.20

Because the first indication of the occurrence of EBPR in activated sludge systems was observed by Srinath *et al.* in India (Srinath *et al.*, 1959) in a treatment plant where the aeration in the first stage of the activated sludge plant was compromised. They merely noticed that the sludge showed an excessive uptake of phosphorus (beyond that required for biomass synthesis) when it was aerated. It was also shown that it was a biological process since it was oxygen-dependent and it was inhibited by toxic substances.

Solution 1.3.21

The Phoredox system developed by James Barnard (Barnard, 1976) consists of one anaerobic stage (that receives the influent wastewater) followed by one aerobic reactor. Thus, mixed liquor activated sludge is cycled through the anaerobic-aerobic configuration of the system (see Figure 6.20D in Chen *et al.,* 2020). This development built on the pioneering research carried out by Levin and Shapiro (1965) who coined the term 'luxury uptake' to describe the induced biological phosphorus removal in excess of the metabolic needs of activated sludge when alternating anaerobic and aerobic conditions.

Solution 1.3.22

The development of anaerobic wastewater treatment technologies was motivated by the energy crisis experienced in the 1970s together with an increased demand for industrial wastewater treatment. Furthermore, the invention of upflow anaerobic sludge blanket reactors (UASB) by Lettinga and colleagues (Lettinga *et al*., 1980) led to a breakthrough in anaerobic treatment. Not only was this technology feasible for industrial wastewater treatment but anaerobic treatment of low-strength municipal wastewater could also be efficiently introduced in tropical regions of South America, Africa and Asia.

Solution 1.3.23

The main cause was the need to develop more compact wastewater treatment plants since rapid urbanization has led to a lower availability of land. Also industries, often with land limitations, started to treat their own wastewater. This caused the development of a whole range of new biofilm-based processes such as biological aerated filters, fluid-bed reactors, moving-bed bioreactors and granular sludge processes, among others.

Solution 1.3.24

The solid-liquid separation process is carried out by a membrane (either submerged in the main aerobic reactor of the MBR system or located externally). The membrane enables the solids to be retained and produces a clarified treated effluent (Yamamoto *et al.*, 1989).

Solution 1.3.25

The Nereda® process is an aerobic granular sludge technology that allows a more efficient and compact removal of nutrients. To minimize costs, it is a sequencing technology based on the fill-and-draw principles of Ardern and Locket (1914) and Pasveer (1959) so all the biological conversion and settling processes occur in one single reactor.

Solution 1.3.26

One of the main factors was the need to upgrade existing plants in order to comply with the new stricter effluent discharge standards instead of building new treatment systems. Thus, it was observed that considerable nitrogen and phosphorus concentrations were released in the sludge handling facilities, which returned to the main-stream wastewater treatment line through internal recycle flows. The development and implementation of different side-stream processes, which take advantage of the particular characteristics of the side-stream streams (e.g. highly concentrated, higher temperatures and lower flow rates), promoted and facilitated the cost-effective removal of nitrogen and phosphorus. Processes such as the high activity ammonium removal over nitrite (SHARON®), the anaerobic ammonia oxidation (ANAMMOX®) and Crystalactor® (for improved nitrogen removal and mineral crystallization for phosphorus precipitation, recovery and reuse), are some of the technologies that have contributed to these developments.

Solution 1.3.27

In view of an increasing interest in the last decade, in addition to the recovery of water and biogas, cellulose, hydrogen, polyhydroxyalkanoates, nitrogen, phosphates, proteins, extracellular polymers, and even heat, have been identified as recoverable resources from wastewater (Van Loosdrecht and Brdjanovic, 2014).

Solution 1.3.28

The main advantage is to facilitate the operation of existing wastewater treatment plants increasing their reliability to meet stricter effluent standards. It also contributes to a reduction in the operational costs, savings, and recovery of resources.

Solution 1.3.29

Because water reclamation and reuse has been seen as an alternative in order to alleviate water scarcity. Thus, for instance, UV and ozonation technologies (among others) have become increasingly interesting as disinfection processes as well as for the removal of pollutants of emerging concern.

Answer 1.3.30

The main driver is coping with water scarcity and the need to save fresh water through the search and implementation of alternative water sources for non-potable water related activities. This practice relies on the fact that, in current sanitation systems, on average at least one third of the water consumed in a household is used for toilet flushing and does not require water of drinking quality (Chen *et al*., 2012; Van Loosdrecht *et al*., 2012).

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