Chapter 7
The Small-Scale Approach in Wastewater Treatment

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7.1 Introduction

In the middle of the nineteenth century, engineers and natural scientists discovered the outbreak of some fatal diseases such as typhus, cholera and diarrhoea due to the direct contact of human beings with their own excreta containing pathogenic microorganisms [1]. To protect the population and prevent infections, the sewer systems were substantially reinvented going further ancient civilisation experiences.

However, the transport of wastewaters out of human settlements got quickly insufficient because the quality of surface water, to whom the sewage was discharged, started to decrease (*e.g.* hypo/anoxia and pathogens), creating health risks for the population living downstream. So that, intensive and costly purification became necessary, pressing the birth of wastewater treatment facilities.

In general, the heavy industrialisation process and the continuous economic and population growth induced, time by time, the application of more strict water quality standards and the subsequent need to develop and implement wastewater treatment technologies able to satisfy the new requirements.

Normally, the main sources of wastewater originate not only from industrial activities (*e.g.* chemical syntheses, waste gas treatment systems, conditioning of utility water, bleed from boiler feed water systems, blow down from cooling cycles, backwashing of filters and ion exchangers, landfill leachates and rainwater from contaminated areas) but also from urban and commercial settlements, identifying potential

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S.K. Sharma and R. Sanghi (eds.), *Wastewater Reuse and Management*,
DOI 10.1007/978-94-007-4942-9_7, © Springer Science+Business Media Dordrecht 2013

impacts on hydraulic loads, content of pollutant substances, effect or hazardous potential on the receiving water body and effect on aquatic organisms as toxicity.

There are several wastewater treatment techniques to be used singly or in combination with others that should cover all potential needs for wastewater treatment. Separation techniques (*e.g.* grit separation, sedimentation, air flotation, filtration, micro- and ultrafiltration, oil-water separation) are mainly used in combination with other operations as a first or final treatment step. Physico-chemical treatment techniques (*e.g.* coagulation/precipitation/sedimentation/filtration, crystallisation, chemical and wet air oxidation, supercritical water oxidation, chemical reduction, hydrolysis, nanofiltration, reverse osmosis, adsorption, ion exchange, extraction, distillation/rectification, evaporation, stripping and incineration) are primarily used for non-biodegradable wastewaters, inorganic or hardly biodegradable organic contaminants, often as an upstream pretreatment; and biological treatment techniques (*e.g.* anaerobic/aerobic processes, nitrification/denitrification and central or decentralised biological treatments) are considered for biodegradable wastewaters [2]. Specifically, particular attention should be paid to membrane biological reactors and its various potential upgrading. Anyhow, the most challenging technologies are those able to easily adapt to specific situations, increasing the diversity of systems and stressing on their evolution. Indeed, experts are experiencing that there is no system able to cope all the situations such as it occurs in the case of the matter of scale [3].

At the moment, sustainable development is at the forefront of today's policy agendas, and technology developers are focusing on sustainable and best available technologies (BATs) on wastewater treatments and nutrient cycling, not only on a centralised basis but mostly on a small- and medium-sized configuration. Indeed, centralised and decentralised (small- and medium-sized) plants coexisted over the past years, but industrialised countries started to be fond of the small- and medium-scale alternatives [1], due to the poor efficiency of the on-site traditional applications (*e.g.* septic tanks, ponds and wetlands), even though costs could be of main concern. Their legitimation is a crucial task and may strongly influence decision makers and thus subsequent pollution control standards, efforts to preserve resources, maintain and strengthen hygienic standards, increase waste material recovery, recycle and reuse, changes in water consumption and innovative technological applications [4].

The Newman's vademecum [5] provided some wastewater-oriented goals for sustainability such as the ocean and river outfalls made redundant, the recycling of water, nutrients and organics for various uses, the reduction for large pipes requirement and the increase of soft surfaces to reduce urban sprawl for storm water retention. Besides, other options are related to a more far-reaching eco-friendliness as well as energy and nutrient recovery [4]. Currently, the main emphasis is towards the grey water recycling [6] considering various levels of technology, especially best available technologies (BATs), ranging from minimal surface filtration devices with short residence times [7], purely physical membrane processes and to advanced and integrated biological systems [8].

7.2 Does Decentralisation Make Sense?

7.2.1 A Preliminary Brainstorm

Today, in the urban context, centralisation is still the norm in the developed world, while in the developing world, the opposite is generally the case. In the latter, wastewater from houses, businesses and industry remain untreated or are frequently treated on-site and discharged (whether treated or not) to the ground or nearby drains and watercourses [3]. The question facing the communities in the developing world is, however, the same, that is, whether they should install a centralised or decentralised system if they want to deal with their wastewater. Indeed, at now, decentralisation processes seem to be able to satisfy all traditional centralised treatment requirements, presenting at the same time some added values mainly related to the ability of minimising potential residual effluent contamination as well as ecosystem disruption by removing emerging micropollutants such as metals and pharmaceuticals and personal care products [9]. Jefferson et al. [6] highlighted the fact that small wastewater treatment plants (WWTPs) have been starting to play an important role at global level in the management of water quality (*i.e.* rivers, lakes, estuaries and aquifers). Indeed, they are frequently characterised by a greater numerical growth compared to centralised systems [2]. Certainly, in some countries, the total amount of small plants is able to treat a greater volume of wastewater than the existing centralised ones [10].

The international debate upon decentralisation is including several international governmental and non-governmental organisations considering policymakers, local authorities and stakeholders. Actually, this kind of approach involves various economic, social, technological and environmental constraints in the centralisation/decentralisation dichotomy resulting in the fact that there is no possibility to accept or refuse one of them *a priori*, being the necessity to proceed on a case-by-case basis [3]. Moreover, apart for the fact that the major costs in centralisation are absorbed by the collection system [11] and in decentralisation by the suggested treatment technology [12], it might be highlighted that the budgetary aspects cannot be generalised [3].

7.2.2 Small- and Medium-Sized WWTPs: A Step Beyond Centralisation

Small- and medium-sized wastewater treatment plants (SMTPs) are playing a major role, globally, in the local management of water quality for rivers, lakes, estuaries and groundwater, constituting a potential growth market for the next millennium [6] for decentralised treatments as recognised by IPPC [2] in opposition to centralised ones. They are not only very numerous, but in some countries, a much greater proportion of wastewater is already treated in small systems than in large plants

[10] because they seem to have the capacity to make waste treatment more sustainable; certainly, large-scale systems need management, administrative and large monetary requirements to develop the plant, but their effluents are, at the moment, still more cost-effective than SMTP discharges. However, a decentralised system is considered competitive only if it can provide an advanced wastewater treatment, that is highly effective, robust, easy to operate and low in costs, and an adequately trained personnel for its management is available [1].

The matter of scale is strictly related to local regulations and traditional assumptions of the involved categories such as engineers and environmental scientists. As reported in Libralato et al. [3], the Directive 91/271/EEC defined the treatment ability classification at European level basing it on the treated organic load expressed as person equivalent. So, small treatment plants present no unique definition. For the English Institute of Water Pollution Control, a WWTP is small when less than 1,000 p.e. can be treated, whereas the threshold is set at 10,000 p.e. for the US Environmental Protection Agency [13]. De Fraja Frangipane and Pastorelli [13] and Avezzù et al. [14] considered 2,500 p.e. as maximum level to consider a WWTP as small, but evidencing that until 5,000 p.e., the same WWTP configurations could be maintained. Moreover, Libralato et al. [3] evidenced that decentralisation processes are not categorised as well. Indeed, Ho and Anda [15] indicated that a decentralised WWTP would be able to supply <5,000 p.e. that is one order of magnitude greater than the definition for small systems arbitrarily set by the IWA Specialist Group for Small Water and Wastewater Systems as systems treating less than 100,000 L day^{-1}, but still two orders of magnitude smaller than for a centralised system. Besides, the previous definition for small systems given by the IWA Specialist Group on Design and Operation of Small Wastewater Treatment Plants was confuted, meaning that a treatment ability <2,000 p.e. or having an average daily flow <200 m^3 [16] could not be assumed as exclusively referenced to a decentralised WWTP. In decentralised systems, raw wastewater is frequently treated next to the source [1], meaning that wastewater still requires being collected, but the use of large and long pipes and expensive excavations works are avoided [3]. Additionally, decentralised processes could also be classified in three main categories according to Orth [4]: (a) simple sanitation systems (*i.e.* toilets) (*e.g.* pit latrines, pour-flush toilets, composting toilets and aquaprivies), (b) small-scale mechanical-biological treatment plants and (c) recycling systems. The simple-based technology and relative inexpensive sanitation systems (*i.e.* toilets) are asked to minimise sanitary problems by retaining faecal matter and discharging the liquid phase, with control of water pollution being of minor significance. Small-scale mechanical-biological treatment plants present at least a mechanical and a biological treatment step or, otherwise, might offer a natural-like treatment such as ponds and wetlands (*e.g.* phytoremediation pond). Thus, water pollution is contained, and other facilities enhancing nutrient removal, disinfection or solids removal might be upgraded to the system, also by means of membranes. About recycling systems, the top priority regards environmental protection. Particularly, within this approach, it might be stressed on supporting the diversion of wastewater flows while complying with modern hygienic standards, the production of high-quality fertilisers and,

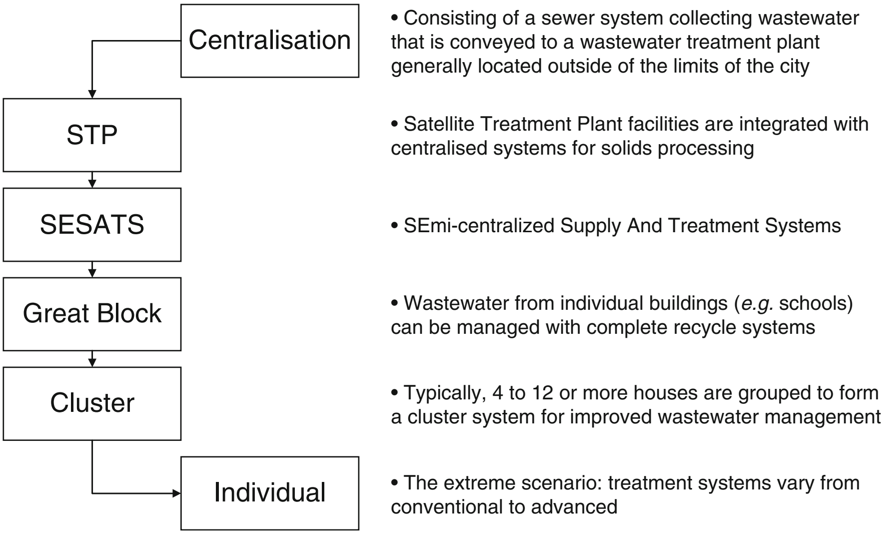

Fig. 7.1 Transition from centralisation to decentralisation [3]

eventually, biogas (*i.e.* anaerobic wastewater treatment processes), as well as the possibility of treated wastewater reuse for non-potable purposes.

Certainly, there still remains a great potential for wastewater flow separation besides urine (yellow wastewater) and faecal matter (brown wastewater) diversion, which are both components of black wastewater. Indeed, it is possible to organise and support the separation, treatment and reuse of white (rain/storm water) and grey wastewater (*e.g.* kitchen, bathtub, washing machine) [17–21].

Furthermore, it must be detailed that frequently the term “decentralised” does not comply with “small”. Indeed, according to Libralato et al. [3], decentralisation can consist of from one to several scaling levels: from individual on-site systems to a series of larger clusters or semi-centralised WWTPs (*e.g.* cluster systems grouping some houses, great block WWTPs, semi-centralised supply and treatment systems, and satellite treatment plants) before approaching the traditional concept of centralised wastewater treatment system as shown in Fig. 7.1.

Several circumstances are strongly influencing the next future of SMTPs such as the population increase in rural areas and developing countries, the increasing impairment of surface water quality, the development of heavily polluted high-rise buildings in metropolitan areas, the development of planned but somewhat isolated communities and the growing shortages of water resources [22]. For example, a possible solution for small communities could be to take into consideration extensive systems with intensive processes. Anyhow, some challenging questions with no obvious or unique answer must be asked before taking the final decision: local or regional solutions for wastewater treatment? If a local solution is chosen, intensive or extensive processes? If an extensive one is preferred, which technological facility is to be selected to meet the goal of regulatory standards? [23].

About 25% of the population in USA (over 60 million) are serviced by on-site and small-scale WWTPs [24], especially those living in rural areas or not served by sewerage and centralised wastewater collection and treatment systems, but also at what time large WWTPs failed or there is a lack of action or capacity by the central governing body. Actually, after several years from the Clean Water Act, it was recognised that complete USA sewerage may never be possible due to geographic and economic constraints [25].

Similarly in smaller countries such as Ireland, the domestic wastewater of over one third of the population is treated by on-site systems, and specific regulations have been implemented to strengthen the environment safeguard (*i.e.* especially of groundwater quality), thanks to the attention of local policymakers on this topic [26, 27].

There has been a general acceptance by stakeholders and professionals of small- and medium-sized wastewater treatment (SMTs) applications because they help the improvement of public and environmental health by minimising the impact of wastewaters, being, potentially, sustainable considering equally, economic, environmental and social topics. Of course, a series of factors needs to be taken into consideration to select the SMTs, such as the population density, the location, the technology and its efficiency, the investment, the operation of maintenance, the protection of environmental quality, the conservation of resources (including the energy use), the water reuse, the nutrient recycling, the protection of public health, the convenience security, the government policy and the human settlement planning [28].

The design methodology of SMT systems is based on the combining effective treatment processes with the commercial demand of the market and the achievement of a high-quality effluent suitable for direct discharge to surface waters.

At the moment, the majority of SMTs are designed to remove carbonaceous compounds and suspended solids, but there is an increasing demand for nitrification and phosphorus removal [29]. Some of the applications of small-scale high-quality wastewater treatment could be for localised storm water treatment and recycling and for water harvesting for local water supply purposes and water appliances; definitely, fittings and technologies could facilitate the achievement of quality goals [30].

The main general characteristics of SMTs are related to economic costs, sustainable resource uses, ecological and human health impacts, system reliability and resilience, and social and institutional implications [31]. They are relative inexpensive, including capital, installation and running costs [32] depending on the technology used, making the use of recovered wastes more practical and cost-effective, especially for small nutrients and water cycles. They can maximise the opportunities for the reuse of sewage components (*i.e.* reuse of treated wastewaters for toilet flushing and watering lawns) [33], decrease the final discharge volume reducing the cumulative impacts to water environments due to the increased potential for reuse [31] and lower the level of pathogen risk to the total community than equivalent centralised reuse [34]. They can make the source stream separation easily applied allowing treatment and reuse of different waste streams (grey and black water and urine) and greater efficiencies [15] saving energy [18]. At the same time, they are able to minimise the potential for nutrients containing residuals to be contaminated with metals and other toxins. They are suitable for remote locations where access to the main drainage is difficult; they are compact, having a small footprint and minimal depth [35], reducing the aesthetic impact (*i.e.* visual, noise and odour) [1] and without any potential for catastrophic impacts on the contrary of large-scale centralised infrastructures [31]. There is no need of extensive piping and pumping systems, but easy operation and maintenance are led on [12]. They have greater flexibility and adaptability to changes and to changing service requirements [36]. Even though the community and ownership are widely involved, there are some negative aspects such as the uncertain regulatory framework in many jurisdictions, the organisational challenges for utilities managing multiple dispersed assets and the perceived actual fluctuating reliability of decentralised systems [31].

Package treatment systems are, generally, preferred for biological processes. There are many process configurations and technologies that could be applied to small- and medium- scale WWTPs such as rotating biological contactors (RBCs); extended aeration activated sludge (EAAS); activated sludge sequencing biological reactors (AS-SBRs); membrane biological reactors (MBRs) and submerged aerated media systems [29, 37]; wet composting and vermicomposting tanks; anaerobic treatments; sand, soil and peat filters; constructed wetlands; and grey, black and urine water separation systems [38]. In particular, modern membrane reactors integrating a suspended growth bioreactor with a membrane filtration device (microfiltration/ultrafiltration, MF/UF) could provide efficient barriers achieving high removal rates: indeed, the membranes retain suspended solids, colloidal and macromolecular materials, including bacteria.

Currently, small-scale applications in the wastewater treatment sector are gaining a great attention both in the developed and developing countries. Brown et al. [39] reported that the city of Melbourne (Australia) with an approximate population of 3.9 million is studying a portfolio of decentralised and on-site design concepts of WWTPs. This strategy was intended to cope with the potential uncertainty in future sewage production and its reuse and the need to prepare for integrated water cycle planning. The existing Melbourne sewerage system is largely centralised, thus about 90% of sewage discharges are conveyed to two major centralised plants. However, several small satellite treatment plants service local urban areas generally more distant from the centralised system. The use of decentralised WWTPs in Melbourne is still rare, but the aim of the future integrated water planning is to combine centralisation with various levels of decentralisation as well as on-site operations.

Orth [4] presented the case study of the Ruhr district (Germany) as an example of how the sewage disposal may evolve according to a sort of ecologically sound adaptive ability. Initially, centralisation represented the first step to solve intolerable hygienic conditions. Afterwards, the need to control pollution and support the regional development besides the existing WWTPs led to a series of about 4,200 small-scale treatment systems creating a composite system made of centralised and decentralised elements.

Libralato et al. [3] highlighted that in Italy, 6% of the population is served by WWTPs with $<2{,}000$ p.e., which represent 73% of existing Italian WWTPs mainly due to the country morphology. Likewise, Venice (Italy) may be considered as an interesting case study about decentralisation. Indeed, this well-known ancient city that was built on a series of 119 islands located in the middle of a 540-km^2 lagoon with an average depth of 0.5 m does not have a real sewage collection and treatment system due to its peculiar urban characteristics, but has a huge number (4,493) of on-site decentralised WWTPs [40] that are mostly remote controlled. Their installation, supported by policy and lawmakers, has been reducing the total load of inorganic and organic contamination, enhancing the general health and environmental status of the lagoon.

Peter-Fröhlich et al. [21] presented a pilot project at European level to separate yellow (*i.e.* urine), grey and black wastewater supporting both environmental and economic-related topics. Indeed, this new approach could allow wastewater treatment in remote areas, having no centralised sewage collection systems, or in new developing or refurbishing urban areas where the existing systems could not be cost-effectively upgraded.

Actually, the main added value is related to the increase of environmental sustainability via treated wastewater and nutrient recovery and reuse such as in the case of public and private garden watering or agricultural uses reducing potable water consumption in the perspective of near future water scarcity. The safeguard of water resources is a really challenging topic that has been frequently stressed on a decentralised basis. Nolde [41] reported the results from a 15-year project developed in Germany about grey wastewater recovery and reuse within great block of buildings (*e.g.* commercial centres) and mainly devoted to toilet flushing. It was evidenced that the technological investment mortgage is of about 5–7 years in the case of the adoption of membrane biological reactors.

Furthermore, it was observed that the separation of flows at source (*i.e.* white, yellow, brown, grey and black wastewaters) might sustain the management of emerging micropollutants such as in the case of pharmaceuticals, which are mainly contained in urine rather than in faecal matter [42]. Indeed, nevertheless, urine contains 15% of the total COD of black wastewater [43]; it was discovered that about 64% of pharms and pharmaceutical residues could be found in urine after a quantitative study about 212 drugs [44]. An extreme application of source separation is represented by the NoMix approach that operates a direct urine separation at source [18, 28, 45, 46]. It is already successfully applied in China in the dry version with more than 700,000 users [45]. Palmér Rivera et al. [47] proposed other interesting options promoting source-separating sanitation systems supporting the design of a blackwater separation system with vacuum toilets in a local folklore centre. The sanitation system consisted of three vacuum toilets and one water-free urinal connected to a collection tank, and greywater treatment in a sludge sedimentation tank before vertical sand filter.

7.2.3 To Decentralise or Not to Decentralise: That Is the Question

Today, the debate about the centralisation/decentralisation dichotomy in wastewater treatment science showed that they might be reciprocally unsuitable on a case-by-case basis: one approach cannot exclude the other and vice versa [3]. The possibilities for wastewater treatment are quite huge, and a sort of transition exists in decentralisation processes moving from individual on-site treatment, to cluster or community type (*e.g.* great blocks), and to satellite treatment and semi-centralised WWTPs. Each type is substantially related to the characteristics and volumes of wastewater to be treated as well as to the possibility of flow separation at source.

When talking about decentralisation, it is not possible to refer to just one technical approach such as the NoMix toilet or any other extreme individual treatment system, but to a range of wastewater treatment facilities presenting a strong scaling transition. In most cases, the adoption of a decentralised approach in highly dense populated areas with an already existing sewage collection system could not be a viable alternative to the centralised treatment. A general clue is not yet available on how to approach decentralisation due to the high number of conditioning variables and the creativity of engineers puzzling their brains to make alternatives to traditional wastewater treatment modes [3]. The most probable suggestion is to support the coexistence of various levels of centralisation and decentralisation in WWTPs considering the potentiality of the full series of decentralised approaches that are currently showing a highly realistic appeal, mainly in the case of great blocks (*i.e.* hospitals, shopping centres, airports, schools) and refurbished urban areas, especially in relation to the new trend of treated wastewater recovery and reuse mainly due to climate change-related phenomena (*i.e.* water drought). Moreover, it is of extreme interest to speculate upon the forthcoming necessity of current centralised WWTPs substitution as well as refurbishment and upgrading of their collection system due to their ageing. Major interventions are estimated to be required every 50–60 years, but no unique solutions have been found whether to keep and/or substitute the pristine centralised facilities, generating potential traffic and other public utility disruption or to introduce some kind of decentralisation in the system. Today, this second option appears to be sometimes more suitable, mainly due to the continual growth of urban areas as well as the increasing demand for water resources. It seems that the use of decentralised and satellite systems will allow treated wastewater recovery and reuse, making them a stable and sustainable water source, especially for those areas that historically suffer or have recently been suffering from water scarcity [3].

Since now, pros and cons of centralisation and decentralisation were elucidated in a scattered way evidencing the fact that economic, environmental, social and technological issues may strongly influence decision makers within their potential choices about the implementation of one approach rather than another. Particularly, Brown et al. [39] highlighted that some releases are of main importance such as the life span of system elements, the estimated capital, the maintenance and operating costs, and the (re)use of energy, residuals and water as well as nutrient budgets [48]. On the basis of Libralato et al. [3], the main advantages and disadvantages on centralisation and decentralisation have been assessed also according to Brown et al. [39] issues and listed as follows. On centralisation, the subsequent statements may be provided from a series of authors:

- The wastewater treatment cost per unit volume is still competitive compared to decentralisation where the wastewater collection system already exists [11, 15, 28, 49, 50].

- Around 80–90% of the capital costs are related to the collection system with potential economies of scale associated to densely populated areas [11, 50, 51].
- It is predicted that the whole collection system or of part of it has to be renewed every 50–60 years, besides the required periodic maintenance, potentially generating disruptions to traffic and other public utilities [50].
- Wastewater treatment generally means "to sanitise", but nutrients and other micropollutants might not be removed [52–54].
- Potential eutrophication phenomena may occur in the receiving water body due to the large volumes of treated wastewater discharged [1, 15, 28, 52, 55];
- Rainwater is frequently drained from residential areas by infiltration into the collection system, potentially causing the lowering of the aquifer [15, 28, 49].
- Diluted wastewater requires more expensive treatment approaches [15, 28, 50, 55].
- Heavy rainfall events or contamination by industrial wastewater may generate overflow phenomena [15, 55].
- Natural disasters such as earthquakes and terroristic attacks may cause disruptions to the system generating strong pollution phenomena in the receiving water body [1, 15].
- Diseconomies of scale are possible where long distances have to be covered or as a consequence of rainwater infiltration [11, 50].
- There is a strong dependency on electrical energy supply that might not be adequate due to an economic or political crisis [1, 11, 50].
- Huge volumes of potable water are required to keep the sewage system clean [1, 11, 50].

Furthermore, on decentralisation, the following reports may be delivered from a series of authors:

- Decentralisation may respond to suburban areas and rural centres, industrial, commercial, residential and (re)developing areas in addition to population growth in rural areas and developing countries [1, 15, 25, 28, 33, 39, 42, 56].
- It tends to stop the decrease of surface water quality [25, 33, 39].
- It may be of some help in the case of great block construction in metropolitan areas, pretreating/treating and reusing wastewater, even if in part, thus limiting the volume of discharged wastewater into the existing sewage collection system and obviating its upgrading to support greater volume loads [15, 28, 39, 56].
- It may contribute in the planning of isolated community development [9, 12, 39, 42] and support treated wastewater recovery and reuse [9, 12, 15, 25, 28, 33, 39, 56–58].
- It reduces or excludes the inconveniences related to the collection of discharges, with much smaller and shorter pipes compared to centralisation [15, 25, 28, 33, 39, 57], being applicable to various levels from individual to community [9, 11, 25, 33].
- Small WWTPs are considered as viable if a medium-high technological level is implemented that is efficient, robust and easy to manage and maintain [25, 33, 58], although some unexpected bad performance was experienced mainly due to their managing [59].

- Small WWTPs are eligible to be easily remote controlled facilitating their management [40].
- Much of the cost could be related to possible economies of scale that could be achieved organising wastewater treatment on a cluster basis such as in Australia [31].
- The cost of technologies in decentralisation is becoming comparable to that of centralisation per unit of treated organic load [31].
- Small WWTPs may assure a greater level of environmental sustainability by supporting the potential reuse of treated wastewater as well as nutrient recovery [9, 25, 31, 33, 39, 48, 55, 57, 58].
- The potential contamination of nutrients to be reused by metals and xenobiotic substances in general could be greatly limited [55, 58].
- Eutrophication events may be reduced [1, 9, 15, 28, 31, 39, 52, 55, 57, 58].
- It may support an easier urine source separation, reducing/removing micropollutants such as metals and other emerging compounds (*e.g.* pharmaceuticals and personal care products) [9, 25, 33, 57, 58].
- Decentralised small WWTPs allow the separation of domestic wastewater and rainwater, avoiding dilution phenomena [15, 28].
- It is possible to operate a separation of contaminants at source, easing their treatment and potential reuse and at the same time increasing treatment efficiency and saving energy [9, 25, 33, 39, 57].
- It is possible to exclude the possibility of domestic wastewater contamination by industrial wastewater as well as the relative sludge produced [9, 11].
- It is possible to maximise the *in situ* reuse of treated wastewater, as a consequence of diminishing the final discharge volume and the potential cumulative impacts on the receiving water bodies [25, 33, 39].
- It is possible to considerably reduce the health risk for the population, also by preventing catastrophic events [11, 25, 33, 39, 55].
- Small WWTPs are suitable for isolated or scattered settlements or in the case where only a small amount of space is available for the installation [11, 39].
- Small WWTPs are generally compact, with highly flexible operating conditions and reduced aesthetic impact [11, 39, 40, 55].

Moreover, other aspects that are directly related to decentralisation approaches involve national security concerns. Centralised WWTPs can be seen as an easy-to-attack target that could seriously affect life in some urban areas, for example, due to the physico-chemical and microbiological contamination of surface water preventing its use as a drinking water source. A series of decentralised WWTPs may considerably reduce the risk and potential impact to the receiving water body without compromising the system functions. Moreover, decentralisation processes might reduce the impact of natural disasters such as a flood, tornado, hurricane, volcanic eruption, earthquake, or landslide that could in this way affect only a limited part of the territory keeping the rest safe [3].

7.2.4 *Having a Decentralised Perspective in Land Planning Activities*

Decentralisation might be supported during decision-making processes if cost, flexibility of land use, maintenance and environmental protection are taken into account with special reference to small communities within which reuse scenarios are generally more feasible [60]. Resource efficiency in wastewater management means not only to recover and reuse treated water but also a matter of optimising the management of resources spent on treatment and transport, the natural resource to protect as well as the capital [61]. Particularly, Chung et al. [62] proposed a model to assess the suitability of decentralisation, showing that it fits best to territories with mixed morphology and scattered urban centres. Comparing a centralised WWTP and a series of satellite WWTPs for a community of 1.2 million inhabitants, economies of scale showed to favour centralisation, except for areas with significantly different heights above sea level, making decentralisation a more suitable option. Innovators must tackle the costs of initial investments in infrastructures, and concerted actions are required with the involved stakeholders. Since now, the centralised model has received huge public capital investments making it sustainable due to the economies of scale that are created. Besides, reducing the technological investment compared to initial expectations could save the major costs that could be required to terminate the collection system. At the moment, in Europe, the water sector management is already oriented towards considering the full costs of the resource and the potential effects of water policy changes, which will be more evident in the near future. Nevertheless, the risk of overestimation of such resources is not risky because the benefits obtained from a good quality aquatic environment are still considered as intangible, which is the main reason for the lack of support for innovation in this sector [3]. Indeed, when water resources are in some way related to public health, tourism, education and research, greater funds might be obtained. These uses that require a high water quality would justify the support for innovation and innovators [63].

7.3 Best Available Technologies

The expression “best available technologies”, which is defined in Article 2(11) of the 96/61/EC Directive [64], is very similar to that of the US Clean Water Act (1972) and its following amendments being “*the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole, where:*

- *‘Techniques’ shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned;*

- *'Available' techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator;*
- *'Best' shall mean most effective in achieving a high general level of protection of the environment as a whole".*

In more general terms, BATs or best available technologies not entailing excessive costs (BATNEECs) can be defined as the best viable mix of technologies, processes, services and ways of management in order to reduce the pollution and increase the efficiency [65]. According to this definition, they should pervade all economic activities and sectors, cutting costs and improving competitiveness by saving energy and reducing resource consumption and so creating fewer emissions and less waste. This definition is essentially in line with that given in Chapter 34 of Agenda 21 [66] for environmentally sound technologies, stating that "*Environmentally sound technologies protect the environment, are less polluting, use all resources in a more sustainable manner, recycle more of their wastes and products, and handle residual wastes in a more acceptable manner than the technologies for which they were substitutes. Environmentally sound technologies in the context of pollution are process and product technologies that generate low or no waste, for the prevention of pollution. They also cover end of the pipe technologies for treatment of pollution after it has been generated. Environmentally sound technologies are not just individual technologies, but total systems which include know-how, procedures, goods and services, and equipment as well as organisational and managerial procedures*" [67]. As a consequence, the selection and the application of the best available technologies should be the right union between growth and the environment. Indeed, [...] *growth and the environment are not opposites, they complement each other. Without adequate protection of the environment, growth is undermined; but without growth it is not possible to support environmental protection* [68].

On the basis of Article 9(4) of the 96/61/EC Directive [64], emission limit values, equivalent parameters and technical measures must be based on BATs, without prescribing the use of any technique but considering the technical characteristics of the installation, its geographical location and the local environmental conditions. Under this point of view, there is the need to strengthen the efforts to improve testing (*e.g.* toxicity bioassays), verify performances and standardise environmental technologies, in order to establish a mechanism to validate objectively the performance of these products, increasing the purchasers' confidence in new environmental technologies (*e.g.* nanotechnologies applied to wastewater treatment). Furthermore, standardisation, preferably at the international level, can stimulate innovation and environmentally friendly practises. A meaningful example is that related to "*the lack of European standards for wastewater reuse that is one of the main barriers to the market uptake of membrane bio-reactors for municipal waste*

Table 7.1 BAT-associated emission levels for final treated discharge without dilution. Only the strictest values are reported ([2] mod.)

Parameter	Performance rates (%)	Emission levels (mg L^{-1} day^{-1})
SS		10[a]
COD	96	30
Total inorganic N		5
Total P		0.5

[a] Monthly average

water treatment. Membrane bioreactors have several environmental advantages over conventional activated sludge plants: they remove recalcitrant micropollutants more effectively and they reduce the amount and toxicity of the resulting sewage sludge. They are currently more expensive but provide an effluent that is ready for reuse. However, as this reuse is not encouraged by any kind of regulation or standard, the market is not as developed as it could be" [65].

Besides, the IPPC [2] provided the basic knowledge about the measures for the determination of the BATs for wastewater and waste gas treatment supporting process-integrated methods for preventing and reducing the contamination. In most cases, they are production- or process-specific measures whose applicability requires a special assessment. The use of BATs in wastewater treatment is especially focused to the end-of-pipe approach, optimising treatment procedures, preventing or minimising mixing of contaminated and uncontaminated wastewaters and considering the fact that it is the application (*e.g.* serial combination of some technologies) and the way of management that could make the difference.

At what time wastewater is discharged into surface water (*i.e.* river, lake or sea, and all other kind of surface water bodies), BATs must present a suitable combination of [2]:

- Avoiding a discharge situation such as excessive hydraulic load or toxic wastewater (*i.e.* potential damages to the river bed, the embankment or the biosphere).
- Choosing the discharge point in order to optimise the dispersion.
- Balancing the wastewater not coming from central wastewater treatment plants (WWTPs) to reduce the impact on the receiving water body and to meet discharge requirement before discharging it.
- Implementing a monitoring system to check the water discharge with adequate monitoring frequency.
- Performing toxicity assessments as a complementary tool in order to obtain more information on the effectiveness of the control measures and on the hazard assessment for the receiving body. Generally, a case-by-case basis application is required.

Some emission level requirements for final wastewaters discharged without any dilution into surface water after BAT treatment are reported in Table 7.1.

7.4 Advanced Technologies Potentially Supporting On-Site Water Reuse

The contaminants in wastewater can be removed by physical, chemical and biological means according to a number of different treatment, disposal and reuse alternatives and their relative optimum combination.

Physical unit operations are characterised by the prevalence of physical forces during the treatment operations and were firstly used for wastewater treatment. The main physical processes are screening, mixing, flocculation, sedimentation, flotation and filtration.

In chemical unit processes, the wastewater treatment is obtained via the addition of chemicals or by other chemical reactions. Coagulation, precipitation, gas transfer, disinfection and adsorption are the main chemical unit processes. Both physical and chemical unit operations are, mainly, used to treat non-biodegradable wastewaters and inorganic or hardly biodegradable organic contaminants. On the other hand, biological treatment is primarily used to remove the biodegradable organic substances, basically, converting them into gases released to the atmosphere and into cells removed by settling. Specially, the activated-sludge process is a treatment process that is running since 1914 when Arden and Lockett firstly approached it. Many versions of the original process are in use today, but fundamentally, they are all similar [69].

Generally, unit operation and processes are grouped together to provide what is known as primary, secondary and tertiary (or advanced) treatments. Essentially, the term primary refers to physical unit operations, secondary refers to chemical and biological unit processes and tertiary refers to the potential combination of all three [69].

In this section, the attention is focused on the description of the basic knowledge of some secondary (chemical coagulation/precipitation, activated-sludge sequencing batch reactor, ultrafiltration membrane biological reactor) and, for the most part, tertiary processes (nanofiltration, reverse osmosis and activated carbon) that might support treated wastewater recovery and reuse. These wastewater treatment technologies can also be ranked according to their biodegradability-dependency. In fact, biological treatments are highly dependent from the biodegradable fraction of wastewater, while little influence is exerted on physical (*i.e.* filtration, adsorption, Reverse Osmosis) and chemical processes (*i.e.* precipitation).

7.4.1 Chemical Coagulation/Precipitation

Chemical coagulation and precipitation are well-known methods of wastewater treatment for soluble non-biodegradable contamination since the end of nineteenth century. In most cases, lime is used as a precipitant, generally, in combination with calcium chloride, magnesium chloride, alum, ferric chloride, ferrous sulphate or charcoal. Nowadays, the chemical coagulation and precipitation are mainly used as a means of improving the performance of primary settling facilities, a basic step in the independent physical-chemical treatment of wastewater (*i.e.* heavy metals removal) and for the removal of phosphorus [69]. The chemical coagulation and precipitation are treatment techniques recognised as a BAT in relation to some specific applications [2].

7.4.2 Activated Sludge Sequencing Batch Reactor (AS-SBR)

In recent years, AS-SBR technology received increasing attention worldwide, and a great number of plants have been built [70]. The AS-SBR has been accepted as an alternative to more conventional activated-sludge systems for a wide range of industrial and non-toxic biodegradable wastewater treatments [71, 72], even though it can present some low removal rates for some recalcitrant organic compounds [73]. Anyway, it is seen as one of the most promising processes from SMTPs [70, 74–77]. Goronszy [78] showed that AS-SBR is especially suited for wastewater treatment application characterised by intermittent flow and loading conditions, or in decentralised drainage locations for small population equivalent wastewaters [29, 37].

The AS-SBR is an activated-sludge process; this means that the removal of carbonaceous BOD, the coagulation of non-settleable colloidal solids and the stabilisation of organic matter are accomplished biologically using a variety of microorganisms, principally bacteria. The microorganisms are used to convert the colloidal and dissolved carbonaceous organic matter into various gases and into cell tissue. Therefore, the cell tissue, having specific cell gravity slightly greater than that of water, can be removed from the treated liquid by gravity settling. Other applications are related to nitrification/denitrification and stabilisation processes. Operationally, the organic wastewater is introduced into a reactor where an aerobic/anaerobic bacterial culture is maintained in suspension, constituting the mixed liquor. In the reactor, the bacterial culture carries out the degradation of the wastewater organic fraction, and, after a specified period of time, the settling phase takes place to allow the separation of the cells (as sludge) and of the treated wastewater. Generally, the level at which the biological mass is kept in the reactor depends on the desired treatment efficiency and growth kinetics and is monitored taking into consideration the mixed liquor suspended solids (MLSS) and the mixed liquor volatile suspended solids (MLVSS, *i.e.* a rough approximation of the amount of organic matter present in the solid fraction of wastewater).

The AS-SBR can accomplish the tasks of primary clarification, bio-oxidation, and secondary clarification within the confines of a single reactor in the time-oriented configuration [35], whereas the space-oriented is characterised by at least two reactors where all the treatment processes are serially administered. In particular, the desired effluent quality can be delivered operating on fill/reaction ratios, aeration periods and mixing cycles [79]. The operating cycle of AS-SBR is determined both by degradation and settling performances [80].

Generally, a full AS-SBR sequence is composed of five serial steps: feed, mixing, aerobic reaction, settling and drawing. During the feed and the mixing period, denitrification and phosphorus release take place, while phosphorus uptake, carbonaceous BOD removal and nitrification occur in the following oxidation stage. In addition, endogenous denitrification should take place during the settling phase [70]. Generally, the SS concentration is around 10 g L^{-1} with a sludge retention time from 5 days to more than 30 days [73].

The AS-SBR is able to mitigate the effects due to physico-chemical variations in the wastewater feed flow because the reactor acts also as a surrogate of an equalisation tank; the clarification phase is quicker because the sedimentation is allowed in the same reaction basin (*i.e.* in the AS-SBR time-oriented configuration), and there is an increase in the O_2 transfer during the feeding phase due to the entrance of untreated wastewater rich in biodegradable organics [81]. Manning and Irvine [82] stated that microorganism activity in AS-SBR is greater than through flow processes, and maintenance and management are reduced to a minimum [81] due to the absence of sedimentation basins, the possibility of controlling bulking phenomena modifying the feeding phase [83] and the potential for saving energy, especially, for the treatment of domestic wastewaters produced by small- and medium-sized communities [84].

In particular, the AS-SBR technology at small- and medium-sized municipal treatment plants has increased since 1970s [71], also for retrofitting small works [85] and for some applications to industrial wastewaters (dairies and wineries) [72] or for dealing with piggery effluents [86]. The AS-SBR exists both in the anaerobic/aerobic configurations, providing effluents very low in organic compounds and nutrients, potentially, meeting strict effluent standards. Moreover, this technology could be suitable for rural areas, where experts in WWTP management are rather limited, via the introduction of automatic remote controls [70].

7.4.3 Membrane Biological Reactor (MBR)

Research studies about the application of membranes to biological processes for wastewater treatment started more than 40 years ago, and since about 20 years, they are commercially available. The membrane bioreactor is one of the most promising large-scale newer technologies for providing high-quality effluents (MBR) that has already been classified as BAT by IPPC [2] for its physico-chemical performances and for its potential for retrofitting existing WWTPs.

MBRs coupled to various filtration devices (*e.g.* MF and UF) are a further development of the conventional ASP, where the secondary clarifier is replaced by a membrane filtration [87], for domestic, urban and industrial wastewater treatment. Effluents from MBR plants could cover a range of reuse applications such as irrigation (*e.g.* agriculture and landscape), recreation and environmental use (*e.g.* lakes and ponds), groundwater recharge, if toxicity free, and industrial use [31].

Nevertheless, the MBR has been around since 1960s; it has seen significant advances since the early 1990s. It can be defined as a combined activated-sludge biological (previously described for the AS-SBR) and physical process technology for solid/liquid filtration, integrating suspended growth reactors with membrane filtration, which can be considered as the bottleneck of the process. In a conventional secondary clarifier, only the fraction of the activated sludge that settles as flocks can be retained, but in a MBR, all components of the biomass that are larger than the membrane cutoff are retained. However, the fundamental differences in the biology of an MBR compared to an activated-sludge process are not yet clear since a limited amount of information is available on the way in which descriptive variables such as the flock structure, respiration rate, species and off gas production are affected by the changes in operation [69, 87].

The pressure gradient across the membrane is the driving force accomplishing the separation. As a result, the separation of biomass from the treated wastewater is independent of biomass sedimentation qualities [88].

The MBR has recognised advantages over conventional biological treatments such as higher quality effluent (particle free), higher mixed liquor suspended solids and less excess biosolids [89], absolute control of solids and hydraulic retention times [88], compactness with smaller footprint, a modular nature which suits small scale and system expansion and upgrade [89, 90].

A small-scale MBR WWTP flow sheet could be characterised by a pretreatment step (screening phase), a hybrid membrane process (*e.g.* MF/UF-MBR) followed by an oxidative post-treatment to yield water for non-potable reuse or a second high retention membrane process plus post-treatment for indirect potable use (*e.g.* toilet flushing). The main costs, benefits and issues for membrane-based technologies for decentralised WWTPs can be summarised in the following list [6, 91]:

- Costs of membrane dropped over the past decade, but membrane technology can still be considered relatively expensive – further cost reductions are expected from machine fabrication and an increasing market for small MBRs.
- Negative economy of scale, although balanced by the modular applicability of that technology allowing plant size from single dwellings to clusters and to suburb plant size.
- Weaknesses related to energy demand and subsequent greenhouse gases emission; energy demand is high than a conventional plant (+20%) because fouling needs to be controlled by air scouring or high shear velocity [31].
- Energy consumption could be reduced via the use of an anaerobic MBR which could be a net energy producer due to biogas generation [92], even though at small scale, it could be probably too complex, but suitable for clusters or medium-sized plants.
- Persistent organic pollutants (*e.g.* endocrine disruptors, pharmaceuticals and hormones) are only partially removed, so post-treatment processes (*e.g.* AOP) could be required to enhance the removal of these species.
- Management problems related to unqualified personnel (*e.g.* the owner itself without any in-depth knowledge).

Anyway, further investments to apply membranes successfully to SMTs are required [6, 69, 87, 91, 93] in order to lower system costs and increase affordability, minimise energy demand, maximise nutrient removal for beneficial use, develop disposal strategies from remaining residuals, develop integrity monitors that are low cost, effective and reliable, establish remote management systems, develop regulatory framework for decentralised non-potable effluent reuse in urban areas and provide wastewater system managers with planning tools that account for the advantages of decentralised systems based on membrane technologies.

There are two main potential configurations of MBRs: the immersed (submerged or outside-in filtration) and the side stream one (inside-out filtration). A submerged system operates at a lower transmembrane pressure (TMP) than side stream membranes and therefore at a lower flow.

In most membrane processes, it can be said that there are three main streams: a feed, a retentate (unpermeated product) and a permeate. If there is no retentate, the filtration is termed dead-end, vice versa it is termed crossflow.

The membrane productivity is expressed as the permeate flow through the membrane that is reduced along the operating time due to fouling [94]. The fouling control in the submerged membranes is achieved by an air scour at the membrane surface by coarse bubble crossflow aeration. The movement of the bubbles close to the membrane surface causes the necessary shear velocity. At side stream filtration membranes, a high water velocity achieves the fouling control across the filtration channel. In particular, the side stream crossflow configuration employs a tangential flow across the membrane surface which provides a continuous scouring action and hence reduces the membrane fouling layer due to feed stream debris and macromolecules, whereas frequent backwashing is required for the dead-end configuration. Crossflow membranes can provide high system utilisation with minimal plant cleaning downtime. In both cases, the membrane productivity can also be re-established after mechanical or chemical cleaning [91]. However, periodically, chemical cleaning is generally required, and, depending on the type of membrane and treated wastewater, some chemicals such as NaOCl, H_2O_2 and citric acid are used [87, 95]. Its frequency and intensity depend on the loading rate of the wastewater, the bacterial yield, the microbial production of extracellular polymer substances and the retention of non-biological solids in the biofilm matrix [96]. For example, Brindle et al. [97] signalled that membranes do not require any cleaning for over 172 days during the treatment of an ammonia-rich synthetic solid-free wastewater.

Submerged membranes are applied in municipal and industrial WWTPs and can be placed either inside the aeration tank or in an external filtration tank, while the side stream one is mostly used for industrial wastewater treatment. In Venice (Italy), this technology showed to be particularly suitable also for domestic purposes because of its really small footprint, even for real small-scale plants, and its maintenance and management costs [3, 98]. Indeed, there exist more than 140 small-decentralised WWTPs as well as a huge number of septic tanks [40, 99]. Besides wastewater treatment processes, the crossflow side stream membrane filtration can be considered as a mature technology that is also regularly employed as a standard

Table 7.2 Main differences between an activated sludge and an UF-MBR domestic wastewater configuration [87]

Parameter		Activated sludge	UF-MBR
Sludge age	Day	20	30
COD removal	%	94.5	99.0
DOC removal	%	92.7	96.9
SS removal	%	60.9	99.9
Ammonia-N removal	%	98.9	99.2
Total P removal	%	88.5	96.6
Sludge production	KgVSS/COD day	0.22	0.27
Mean flock size	mm	20	3.5

technique for liquid processing to effect clarification, product isolation, concentration and separation duties in a large number of manufacturing industries [100].

The main performance differences between an activated sludge and an UF-MBR domestic wastewater configuration are displayed in Table 7.2. The main advantage of MBR over a traditional suspended growth reactor is the high concentration of MLSS that can be treated leading to small- and high-scale treatment system with reduced sludge production from longer SRTs [91]. The main benefits of membrane technology applied to MBR are related to the selective and consistent separation abilities, the increased product yield, the fact that is an almost well-established technology, and no additives, flocculating agents or pre-coat chemicals are required; besides, large variations in feed quality have little influence on permeate quality; the retrofitting is easy and low maintenance is needed [87].

Membranes with pore size of 0.001–1 μm are typically used [100] with a permeate flow ranging from 15 to 80 L m^{-2} h^{-1} depending of the type of the membrane. Anyway, the pore size of membranes is too large to separate single molecules or ions. The MLSS is independent of the sedimentation behaviour of the sludge, so that it can be increased significantly. Typical values of MLSS are in the range 12–15 g L^{-1} at submerged MBRs and up to higher values for side stream systems [87, 101, 102], keeping in mind the problems related to the oxygen gas-liquid mass transfer. Anyhow, operating MBRs at these conditions can, frequently, create serious problems because high aeration rates are required to provide adequate oxygen supply and effective membrane scouring is difficult to achieve due to the increased mixed liquor viscosity [103]. Besides, by the loss of the secondary clarifier and increase of MLSS in the aeration tank, the footprint of the treatment plant is significantly smaller.

The hydraulic load and the achievable flow are the key parameters for the design of the membrane surface in order to allow the membranes to permeate the maximal flow. The food to microorganism ratio is the key parameter, and as high MLSS can be achieved, the resulting tank volumes are smaller. One advantage of this process is the complete removal of suspended solids and bacteria, including greater viruses [87]. Actually, MF and UF membrane provide from log 2 to log 5 virus removal, respectively, [104] and >log 5 removal protozoa [105]. Indeed, virus removal in wastewater treatment is receiving increasing attention because of the epidemiological significance of viruses as waterborne pathogens [106–108]. Generally, secondary

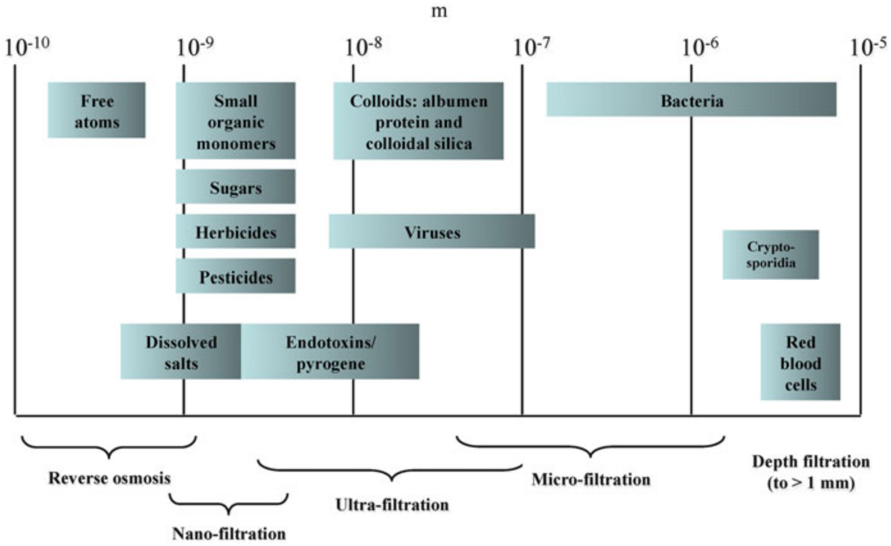

Fig. 7.2 Rejection capability of membrane separation process ([87] mod.)

treatments such as physico-chemical coagulation/precipitation (chemical coagulation/ precipitation and sedimentation) and biological treatment are able to remove 99.9% of faecal coliforms, whereas the removal of viral indicators (*e.g.* bacteriophages) is much lower [109, 110].

About energy consumption, the MBR performances are dependent on many factors such as the plant design, the operational philosophy and the plant size. MBR power requirements come mostly from pumping feed water, recycling retentate, the occasional suction of permeate and the aeration [111]. Generally, the overall energy for submerged systems tend to be lower than for side stream operations [87]. For example, Lesjean et al. [112] stated that a hollow-fibre submerged MBR requires an amount of energy of 0.3–0.6 kWh m^{-3} with a design flow of 20–30 L m^{-2} h^{-1} and a crossflow side stream of 2 –10 kWh m^{-3} with a design flow of 70–100 L m^{-2} h^{-1}.

7.4.3.1 Micro-, Ultra-, Nano- and Reverse Osmosis Filtration

Membrane filtration processes can be divided into groups, based on separation of the respective particle diameters. Fig. 7.2. presented an overview of the diameter application range for the different filtration techniques from Stephenson et al. [87] modified. The following classification is also used in order to categorise crossflow membrane filtration. There is no fixed demarcation between each group. For example, a tight UF membrane made by one manufacturer may be regarded by a second one as a loose NF and so on. All MBRs are generally classified in accordance with the filtration unit separation capabilities.

Table 7.3 Treatment efficiency of MF- and UF-MBR processes [87, 95]

Parameter	MF (%)	UF (%)
BOD	75–90	≈81
COD	46–70	70–85
SS	95–98	97–99.5
Total N		≈12
Ammonium-N	5–15	
Total P	≈14	≈26
Turbidity	92–99	>99
Total coliforms	90–100	100
Faecal coliforms	95–100	100

Microfiltration is a membrane filtration process designed to retain particles in the range 0.10–5 μm with typical operating pressures from 0.5 to 3 bar and is mainly considered as a clarification technique [113] for separation of suspended solids from water and wastewater. Common applications include degreasing processes, metal particle recovery, metal plating wastewater treatment and sludge separation after activated-sludge process [87].

Ultrafiltration membranes have a pore size in the range 0.005–0.1 μm and typical operating pressures range from 0.5 to 5 bar. They are used for separation of both large, dissolved solute molecules and suspended colloidal particles. In particular, its applications include removal of non-toxic degradable and toxic nondegradable pollutants, segregation of oil-in-water emulsions, separation of heavy metals after complexation/precipitation, separation of components not readily degradable in STWs and pretreatment step prior to reverse osmosis or ion exchange [87]. Both MF and UF present high separation efficiency with a high flexibility in usage due to the modular system composition. Sometimes, clogging phenomena can occur, like compaction events due to the presence of softening agents. The MF- and UF-MBR treatment efficiencies for some parameters are reported in Table 7.3. [2].

All membranes are available in several materials, which are directly related to the specific nature of the wastewater, since the resistances are material-specific, and to the required pore size. MF and UF membrane materials are mainly composed of cellulose acetate, glass fibre, polyamide, polycarbonate and polyvinylidenfluoride (PVDF). PVDF membranes have the advantage to be easily cleaned with strong acids, caustic soda and bleaches and, after that, to be immediately ready for reuse [2, 87].

Nanofiltration is an end-of-pipe filtration technique formerly called “leaky reverse osmosis”, mainly, for the removal of soluble non-biodegradable and inhibitory contaminants, and already recognised as BAT by IPPC [2] and GURI [73] for some specific applications.

The separation is achieved through a combination of charge rejection, solubility-diffusion and sieving (0.01–0.001 μm). NF has high separation efficiency, modular systems (*i.e.* flexible in usage), low operating temperatures and possibility of fully automatic operation enabling the immediate recycling of permeate. Conversely, clogging, plugging and fouling processes can occur, like compaction in the presence of softening agents, and high pressures are required producing low permeate flows [2]. NF membranes are composed of cellulose acetate and polyamide [2, 87].

It is used for the removal of dissolved materials in the molecular range of 100–500 D molecular weight. Monovalent species are transmitted through the membrane preferentially. Besides wastewater applications, it is used for partial desalination, for final removal of degradable and toxic components and heavy metals, for removal of sucrose and egg albumin, for segregation of pollutants with the aim of concentrating or further processing them and for blood osmosis and blood filtration [87]. Active nanofiltration might also refer to the application of engineered nanomaterials for wastewater treatment. Indeed, active nano-based wastewater treatments showed to be able to administer not only a physical but also a chemical treatment such as in the case of nano-TiO_2 or nano-zerovalent iron upgraded membranes [114].

Conventionally, osmosis is defined as the net movement of water across a selectively permeable membrane by a difference in osmotic pressure across the membrane itself. Conversely, RO uses hydraulic pressure to oppose and exceed the osmotic pressure of an aqueous feed solution to produce purified water [115]. RO, classified as BAT by IPPC [2] and GURI [73] for some specific applications, is one of the several demineralisation techniques applicable to the production of water suitable for reuse, presenting the added benefit of removing dissolved organics but showing, generally, greater costs and a lack of operating experience on the treatment of domestic wastewater than more traditional techniques [69].

The basic components of a RO unit are the membrane (0.01–0.0001 μm), a membrane support structure, a containing vessel and a high-pressure pump. RO units can be arranged either in series or in parallel and provided of various types of membrane configuration supports (spiral-wound, tubular, plate and frame and hollow-fibre).

RO processes are generally operated crossflow on an end-of-pipe basis, that is, the permeate is directly perpendicular to the feed flow. So that, the impurities remain in the feed which, reducing in volume, leaves the membrane system as a concentrated waste stream [2]. A very high-quality feed wastewater is required to prevent clogging phenomena and improve the efficiency of the membrane, so that pretreatment of a secondary effluent with filtration and AC are necessary, like the removal of iron and manganese in order to decrease the scaling potential. Also, the pH should be adjusted in the range 4.0–7.5 for the same reasons.

RO presents several applications such as the treatment of outflows containing colourings with their possible recovery, oily emulsions, latex and electrophoretic paints and wastewater from the metal-finishing industry with recovery of concentrated solutions of metal salts and reuse of the water in cleaning. Moreover, some industrial sectors, such as precision microelectronics, use the RO process together with treatment using resin exchangers to obtain very pure water [87].

Advantages and disadvantages are more or less the same of NF, with some more restrictions like the treatment of salt solutions with low solubility tending to precipitate and thus causing fouling or contaminants tending to polymerise for the same reason. Moreover, solutions with too high osmotic pressures frequently exceed the operating pressure, and their treatment becomes not economically viable [2].

An example of a multi-application of membrane technologies is that reported by Fane and Fane [31] and summarised in Fig. 7.3. The flowchart shows a pretreatment

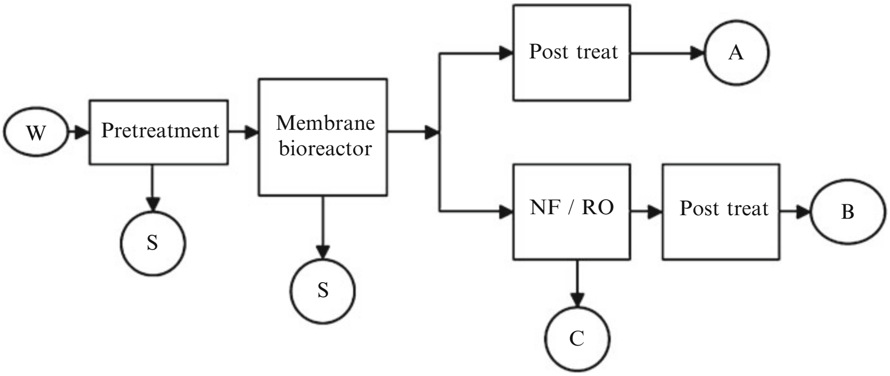

Fig. 7.3 Generic view of wastewater treatment for reuse with membrane processes; usage *A* (high quality); usage *B* (very high quality); *C* concentrate; *S* solids; *W* wastewater [31]

step, tailed by a membrane process (*i.e.* MF/UF-MBR) that is followed by either oxidative post-treatment to support water for reuse (A) (*i.e.* irrigation and non-potable uses) or by a second membrane process (NF/RO) plus post-treatment for further reuse potentiality (B) (*i.e.* non-potable or indirect potable).

7.4.4 Adsorption via Activated Carbon (AC)

Activated carbon is an adsorption medium used to allow the transfer of substances in the water phase to a fixed surface and is classified as one of the end-of-pipe techniques. It is commonly used to remove non-polar organic contaminants, humic substances [95] and refractory compounds to very low concentrations [69]. The adsorption of substances onto AC can be predicted on the basis of their K_{ow} coefficient; substances with $K_{ow} < 0$ are not retained by AC [95]. In Europe, little long-term continuing research has been performed looking at the application of AC filtration for the removal of organic contaminants, pesticides, hormone disrupters and pharmaceuticals, but not clear conclusions are available [95].

In the AC filtration, the effluent is led over a bed of AC in the granular form (GAC) or mixed within the reactor in the powdered one (PAC). In the case of GAC, several filters are serially used. Depending on the bonds between adsorbate and adsorbent, the process could be reversible or irreversible; however, the adsorbent has a finite capacity for each compound to be removed. When the capacity is exhausted, the adsorbent is spent and has to be replaced by fresh material. The spent material can be regenerated or incinerated and finally disposed. Pretreatment for the removal of SS is always required to prevent clogging of the column [95].

The adsorption via AC is a treatment technique that has been recognised as a BAT with respect to some specific applications [2, 73].

7.4.5 Advanced Oxidation Processes (AOPs)

Advanced oxidation processes are taken into consideration to oxidise complex and recalcitrant organic constituents into simpler end products. Generally, it has not required a full oxidation process, but frequently, partial treatments are carried on in order to render specific compounds more amenable to the following activated-sludge biological treatments, so that they may be also considered as a sort of pretreatment stage. The administration of AOPs might lead to (a) primary degradation (*i.e.* structural change in the parent compound), (b) acceptable degradation (*i.e.* structural change in the parent compound with a decrease in the general toxicity level), (c) ultimate degradation (*i.e.* conversion of organic carbon into CO_2) and (d) unacceptable degradation (*i.e.* structural change in the parent compound with an increase in the general toxicity level) [69].

Typically, AOPs involve the generation and use of hydroxyl free radical (OH^-) that is a strong oxidant allowing the oxidation of compounds with which conventional oxidants (*e.g.* oxygen, ozone, and chlorine) failed. Generally, an excess of hydroxyl free radical starts to react in a nonselective way at normal temperature and pressure with the dissolved constituents until they are completely mineralized. Commonly used technological approaches involve ozone/UV, ozone/hydrogen peroxide and hydrogen peroxide/UV that are able to oxidise refractory organic compounds exerting a disinfecting action at the same time [69].

Acknowledgements The author strongly acknowledges Prof. Francesco Avezzù for his great support and for his contributions and suggestions in the revision of this chapter.

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