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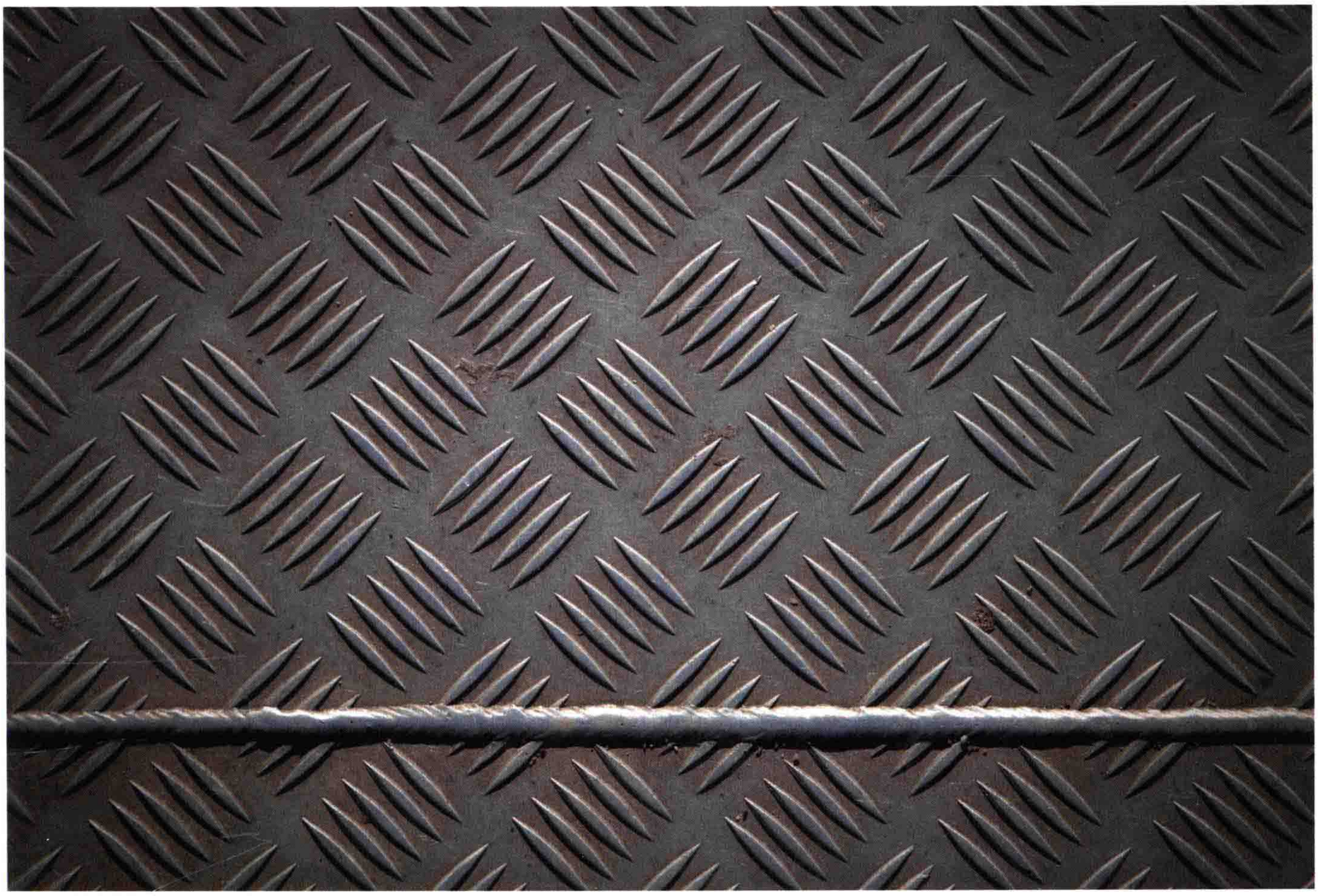
industrial mbrs

membrane bioreactors for industrial wastewater treatment



Simon Judd

industrial mbrs

membrane bioreactors for industrial wastewater treatment

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with Claire Judd

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ABBREVIATIONS

AD	anaerobic digestion
ADF	average daily flow
ADUF	anaerobic digestion-ultrafiltration
AE or Ae	aerobic
AF	anaerobic filter
A-L sMBR	air-lift sidestream MBR
AN or An	anaerobic
An iMBR	anaerobic immersed MBR
An sMBR	anaerobic sidestream MBR
AO or Ao	anoxic
API	active pharmaceutical ingredient
API	American Petroleum Institute
ASP	activated sludge process
BAF	biological aerated filter
BAT	best available technology
BNR	biological nutrient removal
BOD	5-day biochemical oxygen demand
BPR	biological phosphorus removal
CA	cellulose acetate
CAGR	compound annual growth rate
CAPEX	capital expenditure
CAS	conventional activated sludge
CBD	coarse bubble diffuser
CEB	chemically enhanced backflush
CFU	colony-forming units
CFV	crossflow velocity
CIP	clean in place
COD	chemical oxygen demand
CSTR	continuous stirred tank reactor
CTMP	chemical thermomechanical process
DAF	dissolved air flotation
DO	dissolved oxygen
DOC	dissolved organic carbon
DS	dry solids
EPC	engineering, procurement and construction
EPS	extracellular polymeric substances
EQ	equalisation
FBD(A)	fine bubble diffuser (aeration)
Flocs	flocculated particles
F:M	food to micro-organism (ratio)
FOG	fats, oils and grease
FS	flat sheet
GFD	gallons per square foot per day
HDPE	gigh-density polyethylene
HF	gollow fibre
HRT	gydraulic retention time
Hz	Hazen
IAF	induced air flotation
IFAS	integrated fixed film activated sludge
iFS	immersed flat sheet
IGF	induced gas flotation
iHF	immersed hollow fibre
iMBR	immersed membrane bioreactor
LMH	litres per m^2 per hour
MBBR	moving bed bioreactor
MBR	membrane bioreactor
MC	multi-channel
MF	microfiltration
MGD	megagallons per day
MLD	megalitres per day
MLE	modified Ludzack-Ettinger
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
MT	multi-tube
N	nitrogen
NF	nanofiltration
NPV	net present value
O&G	oil and gas
O&M	operation and maintenance
OEM	original equipment manufacturer
OLR	organic loading rate
OPEX	operating expenditure
OTE	oxygen transfer efficiency
OUR	oxygen utilisation rate
P	phosphorus
PA	polyamide
PAN	polyacrylonitrile
PCP	personal care products
PDF	peak daily flow
PE	polyethylene
PES	polyethylsulphone
PP	polypropylene
PS	polysulphone
psi	pounds force per square inch
PTFE	polytetrafluoroethylene
PVA	polyvinyl alcohol
PVDF	polyvinylidene difluoride
PW	produced water
RAS	return activated sludge
RBC	rotating biological contactor
RHS	right-hand side (of equation)
RO	reverse osmosis
SAD	specific aeration demand
SAF	submerged aerated filter
SBR	sequencing batch reactor
SCFM	standard cubic feet per minute
SDI	silt density index
SED	specific energy demand
sMBR	sidestream membrane bioreactor
SMP	soluble microbial product
SOTE	standard oxygen transfer efficiency
SRT	solids retention time
TDS	total dissolved solids
TF	trickling filter
TIPS	thermal-induced phase separation
TKN	total Kjeldahl nitrogen
TMP	thermomechanical process
TMP	transmembrane pressure
TN	total nitrogen
TOC	total organic carbon
TOTEX	total expenditure
TSS	total suspended solids
UASB	upflow anaerobic sludge blanket
UF	ultrafiltration
USCG	US Coast Guard
USEPA	US Environmental Protection Agency
UV	ultraviolet
VOC	volatile organic carbon
VSD	variable speed drive
VSS	volatile suspended solids
WAS	waste activated sludge
ZLD	zero liquid discharge

SYMBOLS

C'_A	oxygen concentration, mg/L
D_{O2}	oxygen demand, mg/L
dP/dt	fouling rate, pressure per unit time
E	specific energy demand per unit volume permeate, kWh/m^3
E_A	specific energy demand for aeration per unit volume permeate, kWh/Nm^3
$E_{A,m}$	specific energy demand for membrane air scouring per unit volume permeate, kWh/m^3
E'_A	specific energy demand for aeration per unit volume air, kWh/Nm^3
$E'_{A,bio}$	specific energy demand for biological aeration per unit volume air, kWh/Nm^3
$E'_{A,m}$	specific energy demand for membrane air scouring per unit volume air, kWh/Nm^3
E_{contr}	specific energy demand for process control per unit volume permeate, kWh/m^3
E_L	specific energy demand for liquid/sludge pumping per unit volume permeate, kWh/m^3
$E_{L,bio}$	specific energy demand for biological aeration per unit volume permeate, kWh/m^3
$E_{L,chem}$	specific energy demand for chemical cleaning per unit volume permeate, kWh/m^3
$E_{L,m}$	specific energy demand for permeation per unit volume permeate, kWh/m^3
$E_{L,sludge}$	specific energy demand for sludge pumping per unit volume permeate, kWh/m^3
E_{mix}	specific energy demand for mixing per unit volume permeate, kWh/m^3
E_{other}	specific energy demand for other operations, kWh/m^3
F_A	specific area footprint, m^3/h per m^2 area (i.e. m/h)
$F{:}M$	food:micro-organism ratio
F_V	specific volume footprint, m^3/h per m^3 volume (i.e. h^{-1})
i	discount rate (rate of return on the investment were the capital sum to be invested)
J	flux, L/(m^2.h)
J_b	backflush flux, L/(m^2.h)
J_{net}	net flux, L/(m^2.h)
k	constant in Equation 10
L	specific cost per m^3 treated water
L_C	specific cost per m^3 treated water for chemicals consumption
L_E	specific cost of electrical energy per kWh
L_L	specific cost per m^3 treated water for labour
L_M	specific cost per m^2 membrane area
L_W	specific cost per m^3 treated water for waste disposal
$O_{2,COD}$	oxygen demand from COD
$P_{A,in}$	inlet pressure, bar or kPa
$P_{A,out}$	outlet pressure, bar or kPa
Q	liquid flow rate, m^3/h
Q_A	aeration rate, Nm^3/h
Q_F	feed flow rate, m^3/h
Q_W	waste flow rate, m^3/h
R	recirculation ratio: recycle flow per feed flow
S_{COD}	COD substrate concentration
SAD_{bio}	specific aeration demand (relating to biological treatment), Nm^3/m^3
SAD_m	specific aeration demand (relating to membrane area), Nm^3/(m^2.h)
SAD_p	specific aeration demand (relating to permeate volume), Nm^3/m^3
$SEDA_m$	specific energy demand for membrane air scouring, see $E_{A,m}$
t	time, membrane life, plant life
t_c	chemical clean cycle time, hrs or d
t_p	physical clean cycle times, mins or hrs
V	tank volume, m^3
X	MLSS concentration, mg/L
y	depth of the aerator in the tank, m
Y	sludge yield, kgVSS per kg COD or BOD
Y_{obs}	observed sludge yield, kgVSS per kg COD or BOD
α	OTE correction factor for solids
β	OTE correction factor for salinity
γ	OTE correction factor for temperature
ΔS	change in concentration of substrate (COD, TKN or nitrate), kg/m^3
λ	ratio of substrate to MLSS concentration
λ_{COD}	biomass COD content, generally ~1.1 kg COD per kg MLSS
λ_{TKN}	biomass TKN content, TKN per g MLSS
k	dimensionless function of temperature
ε	blower efficiency, %
ρ_A	air density, kg/Nm^3
τ_c	chemical clean duration, mins or hrs
τ_p	physical clean duration, s or mins

Preface

An increasing number of books exist based on membrane bioreactor (MBR) technology. Apart from the Butterworth-Heinemann/Elsevier reference texts *The MBR Book* first and second editions (respectively 2006 and 2011), there are also at least two books published by WEFpress (*Membrane Systems for Wastewater Treatment*, 2006, and *Membrane BioReactors WEF Manual of Practice* No. 36, 2011), and a number from IWA Publishing (*Membrane Bioreactors: Operation and Results of an Mbr Wastewater Treatment Plant* edited by Bentem, Petri and Schyns, 2007; Brepol's *Operating Large Scale Membrane Bioreactors for Municipal Wastewater Treatment* from 2010, and the recently published *Membrane Biological Reactors* edited by Hai, Yamamoto and Lee, 2014). The subject of MBRs is included in books on both wastewater treatment/reuse and membrane technology (too numerous to mention, but a recent example encompassing both is Wachinski's *Membrane Processes for Water Reuse*, McGraw-Hill, 2012).

It is, however, notable that many of these books are focused predominantly on municipal rather than industrial effluents. Whilst the MBR technology itself is independent of the application, key design parameters and pre-treatment requirements can differ appreciably and industrial effluents *per se* pose their own challenges. The quality of the effluent varies significantly between sectors, within sectors, and even temporally, diurnally or seasonally for a specific installation. As such the application of MBRs to industrial effluents merits special attention.

As with our previous books we have tried to maintain a practical focus throughout. Indeed, there is no section focused on research and development at all in this book: those seeking such a perspective are directed to Hai et al.'s recent book. Instead, there is a general introduction (Chapter 1), a summary of MBR technology and the key design parameters and cost equations (Chapter 2), a review of industrial effluents (Chapter 3), a compilation of commercially available MBR technologies (Chapter 4) and over fifty case studies (Chapter 5). Processed data from the case studies are presented in the final section of the book.

The terminology and abbreviations are defined in the Abbreviations (x) and Symbols (xi). Units used are exclusively SI: a table of conversion factors for US units is given in Annex 2.

During the course of our research for *Industrial MBRs*, we have been in contact with over 100 contributors from over 60 companies worldwide (page iv). It is therefore almost inevitable that there will be a certain number of (hopefully small) errors and omissions in the text. While we have gone to every effort to try to ensure the accuracy and completeness of the content of this book, please note we cannot be held liable for any errors or omissions. Please notify us at info@thembrsite.com of any issues so we can correct the situation for future editions.

Finally, we would like to thank the many contributors to this book, listed in the Contributors section (page iv), as well as our generous sponsors (page iii). Without their support, both this book and The MBR Site would not be possible.

Simon and Claire Judd

About the author

Professor Simon Judd lectures at Cranfield University in the UK and Qatar University in the Middle East. He has over 22 years' experience in teaching the fundamentals of water and wastewater technologies, and has spent almost 20 years working in membrane bioreactor technology in a teaching, research and consultative capacity.

Industrial MBRs is Simon's seventh book on the subject of water and wastewater treatment. His most recent publications are *The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment* (second edition), published by Elsevier in 2011, and *Watermaths* (second edition), a textbook for undergraduates and practitioners on maths for water and wastewater treatment technologies, published by Judd and Judd Ltd in 2013.

Simon continues to conduct research into municipal water and wastewater treatment generally, also specialising in produced water treatment technologies for the oil and gas sector, and provides consultancy and training on water and wastewater treatment to clients across the globe.

The MBR Site

The MBR Site (thembrsite.com) is a specialist website for those interested in membrane bioreactors for water and wastewater treatment – practitioners, researchers and technology providers.

The website focuses on practical information and guidance, including directory lists of membrane products, technology suppliers, consultants and contractors, and reference installations, as well as Simon's MBR blog and spotlight features on membrane bioreactor technology in practice.

The MBR Site is managed by Claire Judd, co-editor of this book.

The MBR Group

The MBR Group on LinkedIn.com is a lively discussion forum of approaching 5,000 professionals worldwide (as at September 2014), managed by Simon and Claire Judd.

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We would like to thank the following companies (listed here in alphabetical order) for their generous sponsorship of *Industrial MBRs* and for their continuing support of The MBR Site:

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The authors would like to thank the following contributors to *Industrial MBRs*, all of whom have been extremely generous in their time and support for this project. We recognise that there have been a great number of people involved in providing details of industrial sectors, technologies, applications and installations, and that we may have inadvertently omitted to list a number of contributors who also deserve to be included here. If this is the case, we apologise profusely for our oversight, as our intention is not to offend.

A special thanks to Dan Golea at Cranfield University for assisting with the acquisition of data.

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CONTENTS

1 Introduction

1.1 Industrial effluents

Industry accounts for about one quarter of all freshwater demand, and there are few industries which do not consume large quantities of water in generating specific products (Table 1-1). Given that only a limited amount of water is consumed by the industrial process, either through a change in phase (primarily to steam) or inclusion in the industrial product (such as beverages), it follows that a large amount of wastewater is generated by industrial activity. Such waters normally vary in quality temporally (seasonally and/or diurnally), as well as according to the application or duty, to a greater extent than that of municipal effluent (i.e. sewage). Moreover, in many cases industrial wastewaters tend to be more recalcitrant (i.e. biorefractory) than municipal ones, i.e. they are less readily treated biologically and the operating conditions have to be adjusted accordingly.

Table 1-1 Approximate water demand for various items (Waterfootprint, 2014)

Item		*Volume per unit*	*Water demand*
Material	Plastic	-	0.2 L/g
	Steel	100,000 L, car	0.31 L/g
	Bovine leather	300 L, leather jacket	17 L/g
Food	Beer	74 L, glass	0.3 L/g
	Paper	-	0.3-2.6 L/g
	Banana	160 L, large banana	0.8 L/g
	Wine	110 L, glass	0.88 L/g
	Milk	255 L, glass	1 L/g
	Eggs	200 L, egg	3.3 L/g
	Chicken	-	4.3 L/g
	Pork	-	6.0 L/g
	Cotton	2,700 L, T-shirt	11 L/g
	Beef	-	15 L/g
	Chocolate	1,700 L, bar	17 L/g
Power	Uranium	-	90 L/gJ
	Natural gas	-	110 L/gJ
	Coal	-	160 L/gJ
	Hydropower	-	22,000 L/gJ
	Biomass	-	70,000 L/gJ

As well as the discharged effluent, the quality of the influent water demanded by industry varies considerably from one duty to another. For some industrial processes the discharged water quality is not significantly lower than that of the feedwater. Cooling towers, for example, concentrate the water as a result of the evaporative cooling process, but do not add significantly to the pollutant content: the main impact is on the temperature. For most industrial sectors, however, there is a significant pollutant load resulting from their activity, demanding a level of treatment either for safe discharge to the environment or, increasingly, reuse within the process. It is opportunities for water recycling which have to some extent driven the uptake of "high-cost/high-value" process technologies, such as membrane separation, capable of providing reliably high treated water quality. On the other hand, the significant cost of these technologies combined with the challenging timeframe for return on investment usually demanded by most industrial sectors often mitigates against their implementation.

1.2 Industrial effluent treatment processes

The treatment of wastewater relies on a number of individual unit operations which are combined to make a process, or process treatment scheme. The unit operations themselves are fundamentally defined by the principles by which they work. Although process treatment technologies *per se* may be complicated and diverse in practice, their governing principles are largely limited to chemical, biochemical and physical processes (Fig. 1-1). Thus, for example, the simplest physical process is sedimentation, whereby particles are removed from water by settlement in large vessels. This process can be intensified by rotating the vessel, in effect enhancing the gravitational force, such as arises in hydrocyclones and centrifuges. The latter two technologies are very different in configuration to a sedimentation tank, but are nonetheless based on the same fundamental principle.

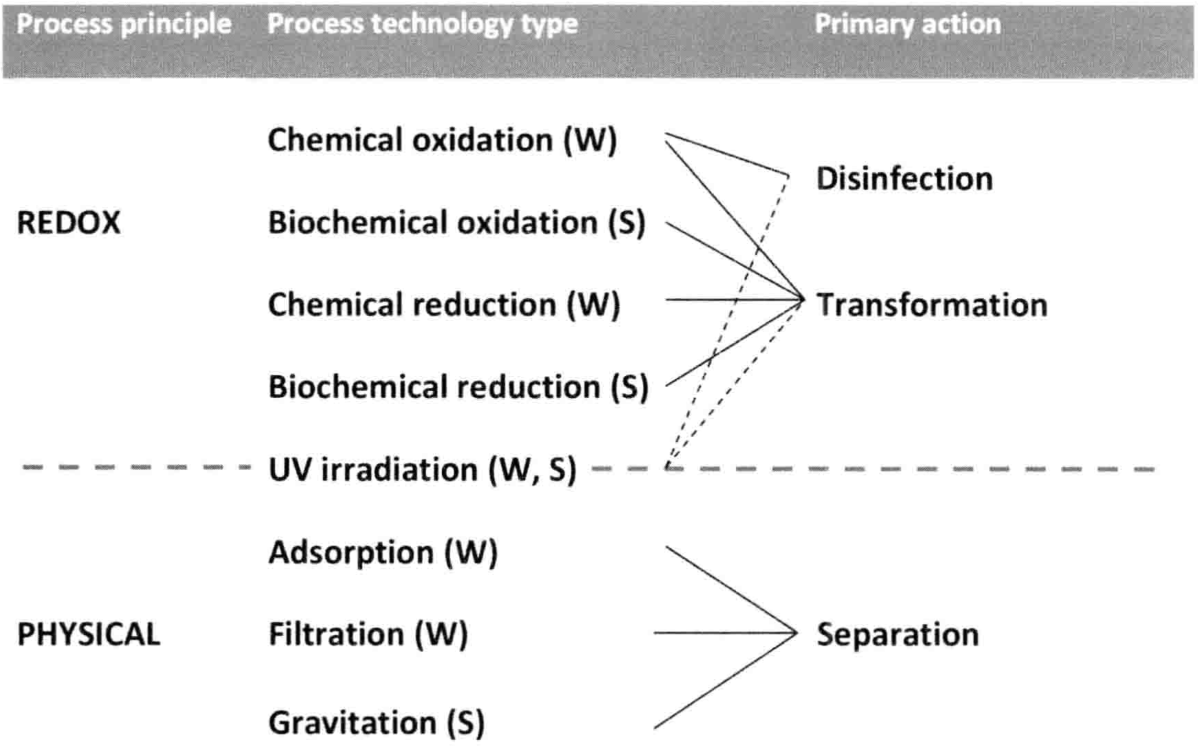

Figure 1-1 Process principles, process technology type, and primary action (W: water treatment; S: sewage treatment)

Chemical and biochemical oxidation processes achieve the same goal but employ different reagents and process configurations. Thus, the pollutant ammonia can be oxidised to nitrate either biochemically using micro-organisms (and specifically "nitrifiers") or chemically using chlorine – a very widely used chemical reagent in the water industry. The chlorination route is relatively rapid, in the region of 10-30 minutes, but leads to the formation of potentially harmful chlorinated by-products. The biochemical process is slow, taking anything between 6 and 48 hours depending on the nature of the feedwater, but is extremely efficient in terms of residual chemical by-products.

These types of reactions fall under the general term "redox", an abbreviation of "reduction/oxidation", since the oxidation of one species must necessarily be accompanied by the reduction of another for electroneutrality to be preserved. Thus processes based on chemical reduction (for example the quenching of excess chlorine using bisulphite) or biochemical reduction (the reduction of nitrate to nitrogen gas) are also examples of the redox principle. However, in the fields of microbiology and biochemistry such reactions are given specific names, for example the biochemical reduction of nitrate to nitrogen is termed "denitrification" and oxidation of ammonia to nitrate called "nitrification". There also exist many important non-redox chemical processes, such as pH adjustment or precipitation of alkaline earth salts (such as calcium carbonate or sulphate).

An exhaustive listing of all individual technologies based on the generic processes shown in Fig. 1-1 is beyond the scope of this book. There are dozens of different technology types, and these may act through more than one process principle. For example, chlorination can both oxidise and disinfect water. A simple slow sand filter combines surface filtration with biochemical oxidation, through the formation of a thick biofilm (or, as it is commonly referred to, "Schmutzdecke") on the filter surface. A membrane bioreactor combines the same two process principles, but the configuration of the technology differs completely from the slow sand filter.

Most biochemical (more usually termed biological) processes are intended to remove organic carbon, since this is the primary food source of micro-organisms generally. Such technologies (Fig. 1-2) can be roughly divided into two categories: "fixed film", where the biomass responsible for carrying out the biochemical reactions is affixed to some medium, and "suspended growth", where the biomass is distributed as particles (or "flocs") in a tank. Some technologies, such as the integrated fixed film activated sludge (IFAS), combine both of these aspects in their design. In this case plastic media are added to the biotank to encourage the growth of a fixed film on the media and thus improve the distribution and the retention of the biomass in the tank.

Biological processes can further be categorised according to the nature of the biology, and specifically the redox reaction (or electron transfer). The latter normally relates to the food source of the micro-organism concerned, which may then in turn depend on the prevailing conditions and, specifically, the presence of a source of oxygen. The conditions are thus generally defined according to whether there is a supply of dissolved oxygen or DO ("aerobic" conditions), an absence of DO but a supply of oxyanions like nitrate ("anoxic" conditions) or the absence of both of these ("anaerobic"). The conditions will then determine the biochemical conversion (Section 2.3.3).

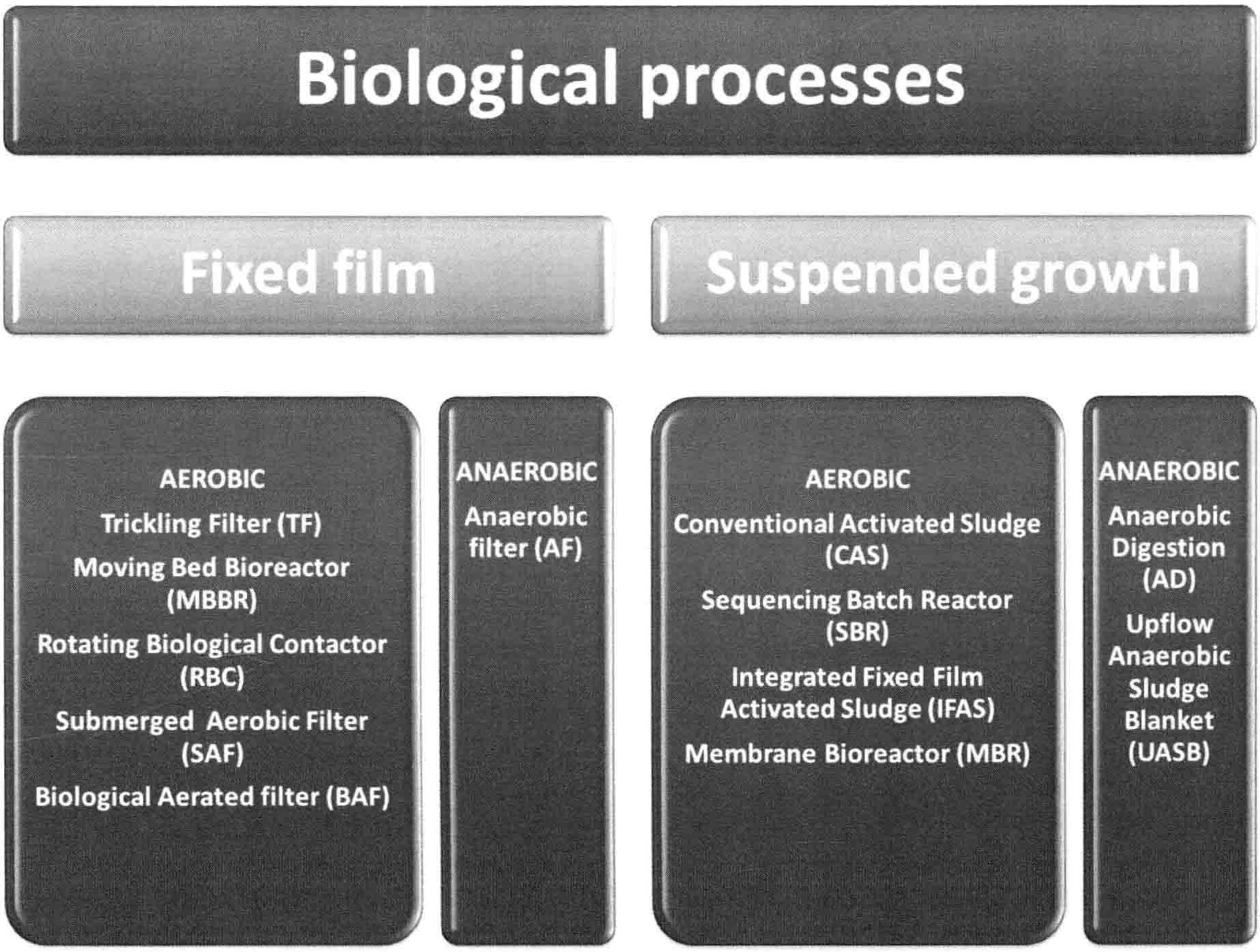

Figure 1-2 Types of biological process technology

1.3 Membrane bioreactors

1.3.1 The MBR technology

Membrane bioreactors (MBRs) are an example of a suspended growth process (Fig. 1-2); although other configurations have been studied they have yet to be commercialised. Whilst most MBR installations operate aerobically, there are examples of anaerobic applications; anaerobic treatment is generally more viable for wastes which have high levels of organic carbon, and is widely used for digesting wastewater sludge. Whilst various process adaptations of the MBR technology have been explored, such as the addition of media to the tank, the basis of the process – the use of a membrane to retain the biomass within a suspended growth biological process – has remained unchanged since its original development.

Membrane bioreactor technology is applied equally effectively to both municipal and industrial wastewater. Municipal MBRs have grown in size over the last decade to the extent that they are now being designed to treat over 350 MLD (megalitres per day), expressed as peak daily flow for municipal feeds, and the trend appears to be for increasingly large installations. Industrial MBRs, by the nature of their purpose, tend to remain relatively small – generally less than 10 MLD - and are designed for specialist applications (Chapters 3 and 5). Therefore, it may be expected for industrial effluent treatment plants not necessarily to increase in size but become more diverse in application, extending to increasingly challenging wastewaters. This tendency is reflected in the number of emerging specialist niche technology suppliers (Chapter 4).

1.3.2 MBR drivers

The drivers for the uptake of MBRs over other advanced wastewater treatment technologies can be summarised as being primarily (a) a requirement for high-quality treated water and (b) spatial restrictions. The process provides the highest quality treated water of all the biological treatment technologies in terms of residual concentrations of suspended inorganic and organic matter (particulates and colloids) and, in the case of municipal effluents, pathogenic bacteria and viruses.

MBRs are particularly attractive in instances where the treated water is to be desalinated by a pressure driven dense membrane process such as reverse osmosis (RO) or nanofiltration (NF). Since very significant removal of colloidal species is attained by the MBR, the RO/NF membrane fouling propensity of the product water – usually represented by the silt density index (SDI) – is very low. Other than the standard protection of the RO/NF membrane by a cartridge filter, no additional treatment of the MBR permeate is required for downstream membrane-based desalination. A number of such reuse plants exist worldwide where the recovered and desalinated water is used for industrial processes, such as steam-raising for electrical power generation, cooling, acid leaching operations or washing/laundering. The reuse of water for purposes where direct human contact is minimal reduces or eliminates the requirement for rigorous disinfection. Data from a recent review (GWI, 2012) suggests that the industrial effluent reuse/desalination market is growing by between 1.8% for the pulp and paper industrial sector to around 17% for the petrochemical and power generation sectors (Fig. 1-3).

The reduced size and footprint of MBR plants over that of conventional biological treatment technologies becomes important when (a) unit land costs are high and/or rapidly increasing, (b) space availability is limited, and (c) legal constraints have been imposed on the installation's visual impact. The latter has led to the housing of MBRs in bespoke buildings (Fig. 1-4) which can be demonstrably unlike those normally associated with conventional wastewater treatment. This particular facet of the technology has strongly influenced its implementation at a number of municipal sites globally, including subterranean installations such as those at Swanage in the UK and Guangzhou in China.