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for a Sustainable Future

Ram Lakhan Singh · Rajat Pratap Singh
Editors

Advances in Biological Treatment of Industrial Waste Water and their Recycling for a Sustainable Future

 Springer

Applied Environmental Science and Engineering for a Sustainable Future

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Advances in Biological Treatment of Industrial Waste Water and their Recycling for a Sustainable Future

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*To
our families
for their abundant support, patience,
and understanding and for their love.*

*To
the students and researchers
who refined our knowledge of biological
sciences
by their intelligent questions, queries, and
discussions
over the years.*

Preface

Water is a scarce natural resource on our planet. Due to rapid industrialization, water pollution problem increased worldwide. These industries use large quantities of potable water for various industrial purposes and release them in the form of wastewater as a by-product. The wastewater generated by different industries has major environmental concern because it contains various hazardous pollutants, and release of wastewater into ecosystem leads to several harmful effects on both flora and fauna. In the present scenario, although it is not possible to stop the release of wastewater in the environment, it is feasible to overcome its harmful effects by its treatment using various methods. The conventional treatment processes have been successfully applied till sometime before, but these methods have many limitations. As viable alternatives, biological treatment methods are becoming more popular day by day; they are cost-effective, eco-friendly, and energy-saving solutions for treatment of industrial wastewater. The aim of biological wastewater treatment is to remove the major pollutants from different industrial wastewater and enable them to be disposed of safely without posing potential danger to the environment and public health as well as to recycle them for various purposes. Wastewater treatment is a very important and interesting area as far as the environmental protection and public safety are concerned because water is one of the basic natural resources for the survival and existence of all living beings.

This book has been developed with the intention of providing an updated source of information on the characteristics and environmental concern of wastewater from various industries and efficient treatment as well as its recycling by biological methods in an environment-friendly and cost-effective manner. The text of this book includes all the dimensions of wastewater treatment methods with detailed account of the biological treatment methods and factors affecting the treatment of wastewater and their recycling. This book is a valuable resource for graduate and undergraduate students, environmental engineers, and others who are concerned with industrial wastewater treatment.

All chapters have been designed and prepared by the authors in such a way that present the subject in depth following a reader-friendly approach. A systematic

reading of the text from the beginning will allow the readers to gain technical concepts of wastewater treatments. The book is easy to follow with simple explanation and a good framework for understanding the complex nature of biological wastewater treatment processes. Overall, this book is certainly a timely addition since the interest in emerging contaminants and wastewater treatment has been growing considerably during the last few years, related to the availability of novel treatment options together with the advanced and highly sensitive analytical techniques.

Key Features

The text of the book includes certain important features to facilitate better understanding of the topics discussed in the chapters.

Abstract at the beginning of each chapter highlights the important concepts discussed and enables recapitulation.

Tables and figures interspersed throughout the chapters enable easy understanding the concepts discussed.

Bibliography at the end of each chapter familiarizes the readers with important texts and articles cited in the text.

Organization of the Book

The book is organized into 11 chapters.

Chapter 1 covers the brief introduction about wastewater released from different industries and their biological treatment.

Chapters 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11 include the characteristics of wastewater released by different industries, harmful effects of wastewater, and their effective treatment to remove the various pollutants present in different industrial wastewater as well as recycling of wastewater for various purposes. These chapters focus on the biological treatment of industrial wastewaters by means of microorganisms and plants.

Faizabad, Uttar Pradesh, India

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August 2018

Ram Lakhan Singh
Rajat Pratap Singh

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Abbreviations

%	Percent
(SO ₄) ²⁻	Sulfate
°C	Degree Celsius
μm	Micrometer
2,4,6-TCP	2,4,6-Trichlorophenol
2,6-DiCH	2,6-Dichloro- <i>p</i> -hydroquinone
6-CHQ	6-Chloro-1,2,4-trihydroxybenzene
ABA	American Beverage Association
ABR	Anaerobic baffled reactor
AC(LB)	Activated carbon (Luria-Bertani)
AC(ME)	Activated carbon (molasses effluent)
Acesulfame K	Acesulfame potassium
AD	Anaerobic digester
ADMI	American Dye Manufacturers Institute
ADP	Alkaline degradation products
AF	Anaerobic filter
AFB	Anaerobic fluidized bed reactor
AlCl ₃	Aluminum chloride
AMBBR	Anaerobic moving bed biofilm reactor
AMBR	Anaerobic migrating blanket reactor
AOP	Advance oxidation process
AOX	Adsorbable organic halides
API	Active pharmaceutical ingredient
API	American Petroleum Institute
AS	Activated sludge
ASBR	Anaerobic sequencing batch reactors
ASP	Activated sludge process
ASR	Active sludge reactor
BAF	Biological aerated filter
BE	Bioreactor effluent

BFA	Bagasse fly ash
BMV	Beet molasses vinasse
BOD	Biochemical/biological oxygen demand
BOD ₅	Biochemical oxygen demand, 5-day test
BTEX	Benzene, toluene, ethylbenzene, and xylene
C:N	Carbon and nitrogen
Ca(OH) ₂	Calcium hydroxide
CAGR	Compound annual growth rate
CaO	Calcium oxide
CD	Corona discharge
CE	Columbic efficiency
CETP	Common Effluent Treatment Plant
CFU	Colony-forming unit
CHPTAC	3-Chloro-2-hydroxypropyltrimethylammonium chloride
Cl ₂	Chlorine gas
ClO ₂	Chlorine dioxide
CMC	Carboxymethyl cellulose
CO ₂	Carbon dioxide
COD	Chemical oxygen demand
CPCB	Central Pollution Control Board
CPI	Corrugated plate interceptor
CP-MAS NMR	Cross polarization/magic-angle spinning nuclear magnetic resonance
Cr (III)	Trivalent chromium
Cr (VI)	Hexavalent chromium
Cr(OH) ₃	Chromium hydroxide
CRB	Chromium-reducing bacteria
CSTR	Continuous stirred tank reactors
CuCl	Cuprous chloride
CuO	Copper oxide
CuSO ₄	Copper sulfate
CWs	Constructed wetlands
Da	Dalton
DAF	Dissolved air flotation
DCE	Dichloroethylene
DCIP reductase	2,6-Dichloroindophenol <i>reductase</i>
DE	Dairy effluent
DEA	Drug Enforcement Administration
DEAE	Diethylaminoethyl cellulose
DF	Drain field
DGGE	Denaturing gradient gel electrophoresis
DO	Dissolved oxygen
DW	Drain well
EC	Electrocoagulation
EC	European Community

Ecb	Electrons from conduction band
EGSB	Expanded granular sludge bed
EO	Electro-oxidation
EPA	Environmental Protection Agency
EU	European Union
$\text{Fe}_2(\text{SO})_3$	Ferric sulfate
Fe^{2+}	Ferrous
Fe^{3+}	Ferric
FeCl_3	Ferric chloride
FMN	Flavin mononucleotide
FOG	Fat, oil, and grease
FT-ICR	Fourier transform ion cyclotron resonance
FTIR	Fourier transform infrared spectroscopy
g	Gram
g/l	Gram per liter
GAA	Glucose-aspartic-acid
GACs	Granular-activated carbons
GFD	Gallons per square foot per day
GGA	Glucose-glutamate-acid
GMO	Genetically modified
H	Hour
H_2O	Water
H_2O_2	Hydrogen peroxide
H_2S	Hydrogen sulfide
HACCP	Hazard analysis for critical control points
HDPE	High-density polyethylene
HORW	Heavy oil-refining wastewater
HPLC	High-performance liquid chromatography
HRT	Hydraulic retention times
HTL	Heat-treatment liquor
$h\nu$	Photon (light)
ICR	Internal circulation reactor
ID	Indirect discharge
IGF	Induced gas floatation
IPPC	Integrated pollution prevention and control
ISI	Indian Standard Institution
JLMBR	Jet loop membrane bioreactor
JLR	Jet loop reactors
K	Kelvin
K_2FeO_4	Potassium iron oxide
kDa	Kilodalton
kg	Kilogram
kg m^{-3}	Kilogram per meter cube
KH_2PO_4	Potassium dihydrogen phosphate
KL	Kiloliter

KMnO ₄	Potassium permanganate
L	Liter
l/kg	Liter per kilogram
LB	Lactose broth
LD ₅₀	Lethal dose
LiP	Lignin peroxidase
LME	Lignin-modifying enzymes
LPG	Liquefied petroleum gas
LTAS	Long-term aerated storage
m	Meter
m/s	Meter per second
m ²	Meter square
m ² /g	Meter square per gram
m ⁻³ d ⁻¹	Meter cube per day
m ³ ha ⁻¹	Meter cube per hectare
MAVF	Macrophyte-assisted vermifilter
MBBR	Moving bed biofilm reactor
mbpd	Million barrels per day
MBR	Membrane bioreactor
MCL	Maximum contaminant level
MDW	Model dairy wastewater
MEC	Microbial electrolysis cell
MF	Microfiltration
MFCs	Microbial fuel cells
mg	Milligram
mg/l	Milligram per liter
MgO	Magnesium oxide
MgSO ₄	Magnesium sulfate
MICs	Minimum inhibitory concentrations
ml	Milliliter
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
mmol/L	Millimole per liter
Mn	Manganese
MnO ₂	Manganese oxide
MnP	Manganese peroxidase
MS	Mass spectroscopy
MSW	Molasses spent wash
MTCC	Microbial Type Culture Collection
mV	Millivolt
NaCl	Sodium chloride
NADH	Nicotinamide adenine dinucleotide
NADPH	Nicotinamide adenine dinucleotide phosphate
NaOH	Sodium hydroxide
NF	Nanofiltration

nm	Nanometer
NMR	Nuclear magnetic resonance
NO _x	Nitrogen oxides
NPK	Nitrogen phosphorus potassium
NR	Not reported
NTU	Nephelometric turbidity unit
NZVI	Nanoscale zerovalent iron
O ₂	Oxygen
O ₂ /L	Oxygen per liter
O ₃	Ozone
OF	Overland inflow
OLR	Organic loading rate
PAC	Powdered activated carbon
PAHs	Polycyclic aromatic hydrocarbons
PBDEs	Polybrominated diphenyl ethers
PBSS	Porous biomass support system
PCBs	Polychlorinated biphenyls
PCP	Pentachlorophenol
PET	Poly ethylene terephthalate
PFS	Polyferric hydroxysulfate
pH	Potential of hydrogen
PMDE	Post-methanated <i>distillery</i> effluent
PPCPs	Pharmaceuticals and personal care products
ppm	Parts per million
PRE	Petroleum refinery effluents
PUF	Polyurethane foam
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
RBC	Rotating biological contactor
RCRA	Resource Conservation and Recovery Act
RI	Rapid infiltration
RM _{oxi}	Redox mediator oxidized
RM _{red}	Redox mediator reduced
RNA	Ribonucleic acid
RO	Reverse osmosis
RPM	Refiner mechanical pulp
RS	Reactive separation
SAA	Sucrose-aspartic-acid
SBI	Sludge biotic index
SBR	Sequential batch reactor
SCADA	Supervisory control and data acquisition system
SCP	Single cell protein
SGA	Sucrose-glutamate-acid
SO ₂	Sulfur dioxide
SOC	Soluble organic substances

sp.	Species
SR	Slow rate
SRT	Solids retention time
SS	Suspended solids
STE	Secondary treated effluent
STPs	Sewage treatment plants
SW	Spent wash
SW	Scouring web
TAN	Total ammoniacal nitrogen
TBA	Tert-butyl alcohol
TCE	Trichloroethylene
TCE	Trichloroethanol
TDS	Total dissolved solids
TDW	Treated distillery wastewater
TeCH	Tetrachloro- <i>p</i> -hydroquinone
TiO ₂	Titanium oxide
TKN	Total Kjeldahl nitrogen
TMP	Thermomechanical pulp
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TPH	Total petroleum hydrocarbon
TS	Total solids
TSS	Total suspended solids
TVS	Total volatile solid
UAF	Upflow anaerobic filter reactor
UASB	Upflow anaerobic sludge blanket
UF	Ultrafiltration
U-MWW	Untreated molasses wastewater
USBF	Upflow sludge bed-filter
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
v/v	Volume by volume
VF	Vermifilter
VFAs	Volatile fatty acids
VP	Versatile peroxidases
w/v	Weight by volume
WAS	Waste activated sludge
WHO	World Health Organization
WQT	Water quality trading
WSC	Water Supply Corporation
XRD	X-ray diffraction
ZLD	Zero liquid discharge

Chapter 1

Introduction



Ram Lakhan Singh and Rajat Pratap Singh

Abstract Freshwater is an imperative normal asset that will keep on being sustainable as long as it is well managed. In many parts of the world, rapid industrial development have prompted to an intensive and still increasing utilization of water resources. Industries are one of the most important pollution sources around the world. The discharge of untreated or improperly treated wastewaters from industries into water bodies may contain very diverse groups of hazardous pollutants depending on the nature of industry. The industrial waste waters may have undesirable color, odour, acids, alkalis, organic matters, toxic chemical contents, heavy metals, pesticides, oils, high biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS) etc. These pollutants may pose a serious threat to all life forms. It is, therefore, necessary to treat the industrial waste water prior to their disposal into water bodies. The conventional industrial waste water treatment processes such as precipitation, adsorption, oxidation, filtration etc. have long been established in removing many hazardous pollutants but these methods have their own limitations. These methods are expensive, and require complex processes and maintenance. Biological treatment process is an important and integral part of any wastewater treatment plant. Different taxonomic group of microorganisms (bacteria, fungi and algae) and plants play a major role in the biological treatment of industrial wastewater. The fresh water demand in current and future prospects could be met by improving the efficiency of water usage and demand management. The recycling and reuse of industrial wastewater is emerging as potential source for demand management and water shortage after essential treatment.

Keywords Industrial wastewater · Pollution · Pollutants · Biological treatment · Recycling

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Rapid industrial growth, urbanization and population explosion are the major contributors of environmental pollution throughout the world. Environmental pollution is a vital concomitant of the activities of man. Wherever we find man, we fundamentally find wastes. These wastes have got to be disposed off and when they are inadequately dumped into the ocean or a river, water resources are contaminated which may pose risk to the aquatic animals and human life. Water has a broad impact on all forms of life. It is a vital natural resource for agriculture, manufacturing and many other human activities. Despite its importance, water is the most poorly managed resource in the world. The accessibility and quality of water always have played an important role in determining the quality of life. There is restricted possibility of an expansion in the supply of fresh water because of competing demands of expanding populations all over the world. Lack of fresh water supply is likewise an aftereffect of the misuse of water resources for domestic, industrial, and irrigation purposes in many parts of the world. Water has certain physical, chemical and biological properties in its natural state. Industrial wastewater may be altering the properties of water which may become unfit for consumption. During the past few decades rapid industrial development has become an important contributor of a country high economic growth. With the development of different industries a large amount of fresh water is used as a raw material. These industries produce a large quantity of wastewater as an essential by-product of modern industry which contributes to water pollution. The surface water is the main source of industries for waste disposal. Water pollution due to improper disposal of untreated industrial effluents into water bodies is a noteworthy issue in the worldwide context. The pollution caused by the release of industrial effluents into the rivers and streams has created the issue of general wellbeing as well as a social issue.

Industrial wastewaters are effluents released from industries which are associated with raw-material processing and manufacturing. Most of the wastewater generating industries include pulp and paper mill, tannery, dairy industry, distillery, winery, sugar mill, textile industry, pharmaceutical industry, oil refinery/petroleum industry, beverages/soft drink bottling industry etc. The wastewaters from these industries may not be safely treated due to the lack of highly efficient and economic treatment technology. Untreated or improper disposal of wastewater have increased the level of surface water pollution resulting in adverse effects on the quality of all forms of life.

1.1 Characteristics of Industrial Wastewater

The wastewaters released by the industries are variable in their composition depending on nature of industry and contaminants. Each industry produces its own particular combination of pollutants. The industrial wastewaters are characterized in terms of their physical (total solids, suspended solids, dissolved solids, color, odour and temperature), chemical (inorganic and organic), and biological characteristics (Table 1.1).

There are various contaminants in industrial wastewater, with organic pollutants constituting the critical part. Numerous organic compounds such as aliphatic and heterocyclic compounds, polycyclic aromatic hydrocarbons (PAHs), polychlorinated

Table 1.1 General characteristics of industrial wastewater

Physical properties	Inorganic constituents
Color	Alkalinity
Odor	Chlorides
Solids	Heavy metals
pH	Nitrogen
Temperature	PH
Chemical properties:	Phosphorus
Organic constituents	
Carbohydrates	Sulfur
Fats, oils, and grease	Gases
Pesticides	Hydrogen sulfide
Phenols	Methane
Proteins	Oxygen
Priority pollutants	Biological constituents
Surfactants	Animals
Volatile organic compounds	Plants
Other pollutants	Eubacteria
	Archaeobacteria

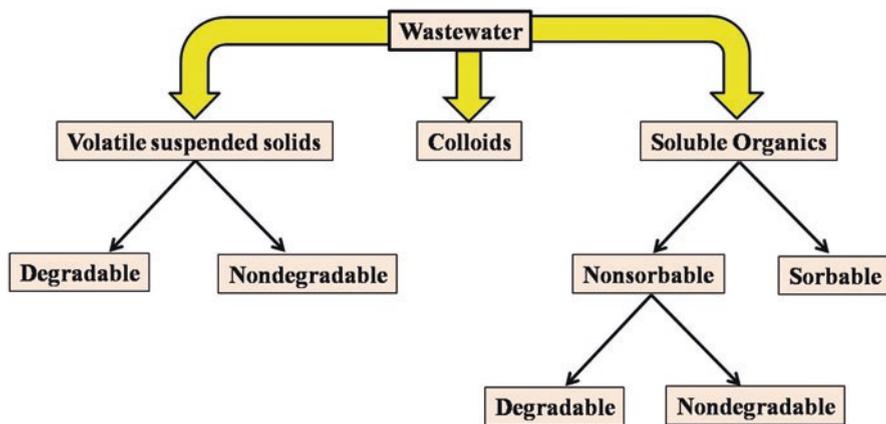


Fig. 1.1 Organic constituents of wastewater

biphenyls (PCBs), pesticides, herbicides, phenols are incorporated in the industrial wastewater. Many inorganic compounds (phosphates, nitrates, sulphates) and heavy metals (Cd, Cr, Ni, Pb) are also present in the industrial wastewater. Large amount of pollutants in water bodies cause an increase in biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS) and total suspended solids (TSS). BOD and COD represent the gross amounts of organic matter and their constituents in wastewater (Fig. 1.1). The pollutants from the discharge are directly related to the nature of the industry. For instance, the wastewater released from textile industry have high COD, BOD and color whereas wastewater released from tannery industry have high concentration of metal such as chromium and cadmium (Table 1.2).

Table 1.2 Characteristics of various industrial wastewaters

Industry	Characteristics of wastewater
Pulp and paper mill	High concentration of suspended solids, BOD, COD, inorganic dyes, chlorinated organic compounds, sodium hydroxide, sodium carbonate, sodium sulphide and bisulfites and wooden compounds such as lignin, cellulose, hemicelluloses
Tannery industry	High concentrations of chlorides, tannins, chromium, sulphate, sulphides, synthetic chemicals such as pesticides, dyes and finishing agents, heavy metals, toxic chemicals, lime with high dissolved and suspended salts, BOD, COD, and other pollutants
Dairy industry	High concentrations of organic material such as proteins (casein), carbohydrates, and lipids, concentrations of suspended solids, BOD and COD, high nitrogen, chlorides and sulphate concentrations, suspended oil and grease contents, inorganic salts, high sodium content from the use of caustic soda, detergents and sanitizers and large variations in pH
Distillery	Color, odour, high concentrations of total solids (TS), TDS, TSS, BOD, COD, ammonical nitrogen, phosphorus, potassium, calcium, magnesium, alkalinity, chloride, melanoidin and large variations in pH
Winery	Organic acids, lees, ethanol, sugars, aldehydes, phenolic compounds, detergents, high BOD, COD, TSS and slightly acidic to basic
Sugar mill	Brown color, burnt sugar like odor, high ash or solid residue, oil and grease, high percentage of dissolved organic and inorganic matter of which 50% may be present as reducing sugars with high BOD, COD, TS, TDS and TSS
Textile industry	High color content with COD and BOD, wide variety of dyes, natural impurities extracted from the fibers and other products such as acids, alkalis, salts, sulfide, formaldehyde, phenolic compounds, surfactants and heavy metals
Pharmaceutical industry	Pharmaceutically active compounds, high BOD, COD, TSS, TDS, TS and high concentrations of acids, phenol, chlorides, nitrogen, sulphate, oil and grease
Oil refinery/petroleum industry	Oil, grease, polyaromatic hydrocarbons (PAH), benzene, toluene, ethylbenzene, xylene, phenols, ammonia, hydrogen sulfide and suspended solids with high BOD and COD
Beverages/soft drink bottling industry	Suspended solids (sac material, juice, pulp and waxes), soluble organics (sugar, and acids), inorganics (caustic soda) and volatile organics (d-limonene from peel oils) with a high BOD:COD ratio, salts of chlorides, phosphate, sulfates, sodium, potassium and calcium, large amount of nitrogen and phosphorous

1.2 Environmental Hazards of Industrial Wastewater

Industrial wastewater is one of the important sources of water pollution. The discharge of industrial wastewater into rivers, lakes and coastal areas resulted in serious water pollution problems and caused negative impacts on the ecosystem and human beings. The industrial discharge carries various types of pollutants such as organic matter, suspended solids, inorganic dissolved salts, petroleum hydrocarbons, heavy metals, surfactants and detergents. These pollutants may pollute receiving water bodies rendering them unsuitable for drinking and irrigation as well as they adversely affects the humans, animals, plants and aquatic life (Table 1.3).

Table 1.3 Adverse effects of pollutants of industrial wastewater

Pollutants	Adverse effects
Alkalinity and acidity	If the permissible range of pH value is violated by the pollutants, it may affect the aquatic life, cause health problems to human and animals and loss of productivity in agriculture
Heavy metals	The accumulation of heavy metals may have adverse effect on aquatic flora and fauna and may constitute a public health problem. Allergic reactions, skin rashes, respiratory tract irritation, gastro-intestinal disorders, renal failure and neurotoxicity are some examples of human health problems caused by heavy metals. Examples of some disease caused by heavy metals: Minamata disease caused by mercury, fluorosis caused by fluoride
Inorganic dissolved salts	Inorganic dissolved salts increase the total dissolved solids (TDS) which may interfere with the use of water in industries, water supplies and for irrigation purposes. Phosphorus and nitrogen are inducing algal growth and create eutrophic condition. The depletion of oxygen by excess algal production giving bad odour and taste of water. They are detrimental to aquatic life and toxic for human and animal life if concentration is beyond permissible limits
Polycyclic aromatic hydrocarbons (PAHs)	PAHs are problematic pollutants of industrial wastewater. They could accumulate in environment and affect the living organisms due of their acute toxicity, mutagenicity or carcinogenicity
Pathogens	Pathogenic bacteria, viruses, etc. are health hazards. Number of water borne diseases may be transmitted by these pathogens such as typhoid, cholera, polio, dysentery, and infectious hepatitis in human beings
Polychlorinated biphenyls (PCBs)	PCBs are carcinogenic and mutagenic in nature and could accumulate in adipose tissue. They may cause internal organs, brain and skin disease. PCBs affect the immune system, nervous system and reproductive system
Pesticides/insecticides	The discharge of pesticides/insecticides containing wastewater could cause serious environmental problem. They are highly poisonous and have acute toxicity on the human beings and livestock. They can damage the liver and affect the respiratory and nervous system. They also play a role in development of Parkinson's disease in humans. In agriculture, they affect the germination of seeds
Petroleum products (oil/grease/oil sludge)	Petroleum products are harmful for soils, aquatic life, animal, human and plant life. Oil spreads over the surface of water resulting in reduction of light transmission which obstructs the photosynthetic activity of the aquatic plants. Accumulation of oily waste affects the aeration and fertility of agricultural land
Phenols	Phenols are toxic to living organisms and impart unpleasant odour. Some phenols such as nitrophenyl are human carcinogens. It also affects plant growth and has potential to decrease the growth and reproductive capacity of the aquatic organisms
Sulphide	It gives bad odour and toxic to animals and aquatic life
Surfactants and detergents	They inhibit the self-purification of water and are harmful for aquatic organisms, animals and humans

Industries produce and utilize a large number of synthetic substances. Many of these substances are recalcitrant in nature which are non-biodegradable or degrade very slowly. Such substances persist in the environment for prolonged periods of time and may, therefore, become progressively more concentrated. These recalcitrant substances are toxic, mutagenic or carcinogenic and may accumulate in the tissues of organisms. These pollutants enter the food chain through bio-magnification and ultimately affect the human beings and other living organisms.

1.3 Treatment of Industrial Wastewater

The treatment of industrial wastewater is classified according to following levels (Fig. 1.2):

Preliminary treatment

It is a separation process and involves the removal of debris and coarse solids.

Primary Treatment

Primary treatment includes the removal of settleable solids (a portion of suspended solids) and part of the organic matter from the wastewater.

Secondary Treatment

The aim of secondary treatment is the further treatment of wastewater from primary treatment to remove the residual biodegradable organic matter, suspended solids and possibly nutrients (Phosphorus and nitrogen) by means of biological process.

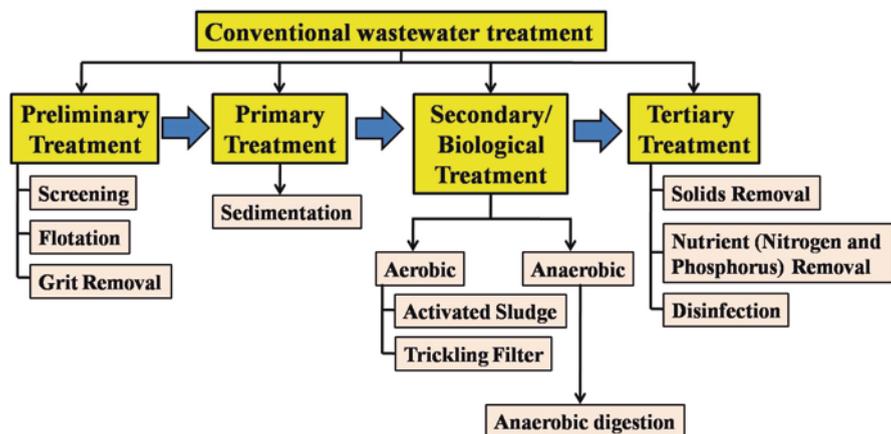


Fig. 1.2 Treatment of industrial wastewater

Tertiary Treatment

Tertiary treatment or advanced treatment is employed for the removal of specific pollutants of wastewater which cannot be sufficiently removed in secondary treatment.

1.3.1 Wastewater Treatment Operations

The wastewater treatment methods are composed of unit operations (Fig. 1.3):

Physical unit operations (Physical treatment)

The wastewater treatment methods in which physical forces are predominant such as screening, aeration, filtration, floating.

Chemical unit operations (Chemical treatment)

The treatment methods in which removal of pollutant occurs by addition of chemical products or due to chemical reactions such as ozonation, coagulation, advanced oxidation processes.

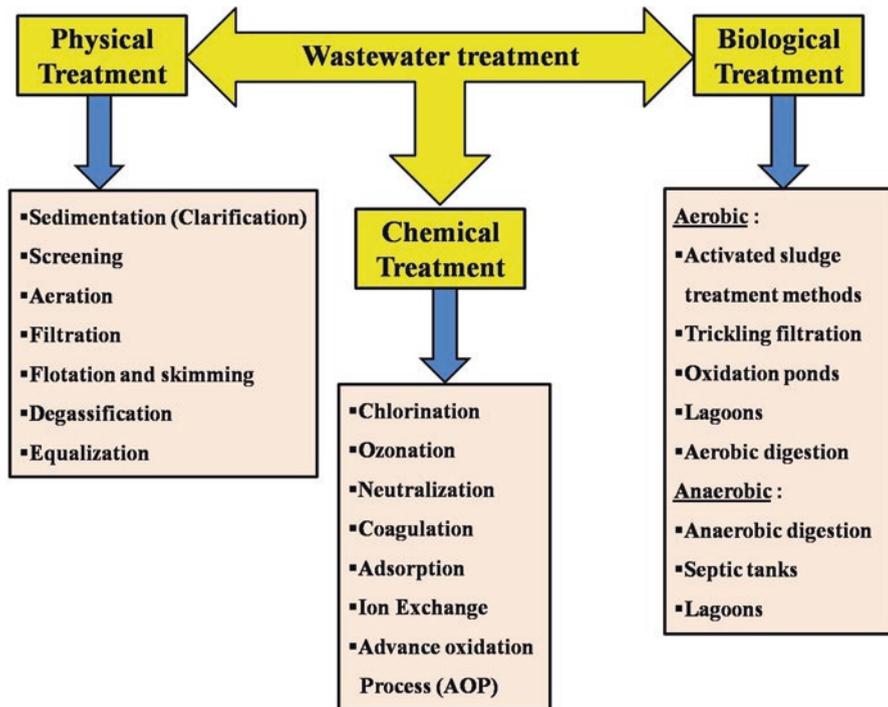


Fig. 1.3 Wastewater treatment operations

Biological unit operations (Biological treatment)

The treatment methods in which removal of pollutant occurs by means of biological activity under aerobic and anaerobic conditions such as activated sludge, trickling filtration and anaerobic digestion.

1.4 Role of Microorganisms and Plants in Biological Treatment of Industrial Wastewater

The wastewater released from various industries contains different pollutants. The discharge of untreated wastewater to natural ecosystems poses a serious threat to all life forms hence affordable and effective methods have become a necessity for the treatment of pollutants present in industrial wastewater. The conventional wastewater treatment system usually involves complicated procedures and is economically unfeasible. The biological treatment processes by means of microorganisms (bacteria, fungi, yeast, algae) and plants may present a relatively inexpensive and environment friendly way to remove different pollutants from various industrial wastewater. The use of biological system to treat the pollutants of industrial wastewater is largely dependent on source and characteristics of wastewater. Microorganisms can break down the pollutants/xenobiotics of industrial wastewater for their growth and/or energy needs. The biological systems have capabilities to remove the pollutants from wastewater by absorption, adsorption and enzymatic degradation processes. A large number of enzymes such as peroxidases, oxidoreductases, laccases, cellulytic enzymes, proteases and amylases from a variety of different biological sources play an important role in the treatment of industrial wastewater.

1.4.1 *Bacteria*

The existence of diverse bacterial populations makes it possible to degrade most of the pollutant of industrial wastewater. The bacterial treatment of wastewater involves the conversion of complex organic matter to harmless simple compounds by aerobic or anaerobic process. The bacteria are frequently applied for the treatment of industrial wastewater because they are easy to cultivate, grow rapidly and suited fine for degradation and even complete mineralization of pollutants. Generally, bacteria obtain their energy from the carbonaceous organic matter (pollutant) of industrial wastewater. Some bacteria used the pollutants of industrial wastewater as their sole carbon and energy source. Several bacteria have been reported in the treatment of various industrial wastewaters (Table 1.4). These bacteria play a major role in phenol degradation, heavy metal removal (chromium reduction from leather industry), dye decolorization from textile industry, decolorization of distillery mill effluent and removal of pollutants of other industrial wastewater such as aliphatic and aromatic hydrocarbons, heavy metals, insecticides and other pollutants by biosorption or enzymatic degradation processes. Few examples of bacteria involved in

Table 1.4 List of some bacteria, fungi, algae and plants involved in biological treatment of industrial wastewater

Bacteria	Algae
<i>Bacillus</i> sp.	<i>Chlamydomonas reinhardtii</i>
<i>Citrobacter</i> sp.	<i>Chlorella vulgaris</i>
<i>Enterobacter</i> sp.	<i>Dictyosphaerium pulchellum</i>
<i>Flavobacterium</i> sp.	<i>Gracilaria</i> sp.
<i>Micrococcus</i> sp.	<i>Lyngbya</i> sp.
<i>Pseudomonas</i> sp.	<i>Oscillatoria</i> sp.
<i>Rhodobacter sphaeroides</i>	<i>Scenedesmus dimorphus</i>
<i>Serratia marcescens</i>	<i>Scenedesmus obliquus</i>
<i>Sphingomonas</i> sp.	<i>Scenedesmus quadricauda</i>
<i>Xanthomonas</i> sp.	<i>Spirogyra</i> sp.
Fungi	Plant
<i>Aspergillus</i> sp.	<i>Acorus calamus</i>
<i>Ganoderma lucidum</i>	<i>Eichhornia crassipes</i>
<i>Geotrichum candidum</i>	<i>Cynodon dactylon</i>
<i>Gliocladium roseum</i>	<i>Euphorbia Prostrata</i>
<i>Penicillium</i> sp.	<i>Helianthus annuus</i>
<i>Phaerochaete chrysosporium</i>	<i>Lemna minor</i>
<i>Trametes versicolor</i>	<i>Phragmites karka</i>
<i>Trichoderma</i> sp.	<i>Pistia stratiotes</i>
<i>Trichophyton rubrum</i>	<i>Ralstonia eutropha</i>
<i>Trichosporon domesticum</i>	<i>Typha latifolia</i>

treatment of pollutants of various industrial wastewaters are as follows: *Aeromonas hydrophila* and *Bacillus* sp. are capable of dye decolorization, *Pseudomonas putida* has potential application for bioremediation of heavy metals, *Sphingomonas chlorophenolica* is capable of complete mineralization of pentachlorophenol (PCP) and *Pseudomonas fluorescence* has capability to decolorize the distillery wastewater.

1.4.2 Fungi

Fungi are multicellular organisms. They have lower sensitivity to variations in temperature, pH, nutrients, and aeration. Fungi have capability to treat the toxic pollutants of industrial wastewater released from various industries into harmless products by biosorption or enzymatic processes. Fungi secrete several isoenzymes which play major role in the removal of pollutants. White rot fungi such as *Phanerochaete chryso-sporium* and *Trametes versicolor* are ubiquitous in nature and their adaptability to extreme conditions makes them widely exploited microorganism in treatment of industrial wastewater. They produce various enzymes including laccases, manganese peroxidases and lignin peroxidases which are involved in the degradation of various xenobiotic compounds. White rot fungi can also remove toxic metals and other pollutants by biosorption process. Their enzyme producing and biosorption activity makes them more effective in the removal of pollutants from industrial

wastewater. Many fungal species are involved in the treatment of various industrial wastewaters (Table 1.4), for example, *Trametes versicolor* and *Rhizopus oryzae* has been involved in treatment of paper and pulp wastewater; *Phanerochaete chyrosporium* has been found effective for color removal from textile wastewater; *Aspergillus fumigatus* has been effective for decolorization of distillery wastewater; *Fusarium oxysporum*, *Cadosporium cladosporioides*, *Gliocladium roseum*, and *Trichoderma koningii* has been involved in removal of heavy metals from industrial wastewater.

1.4.3 Algae

Algae are a diverse group of photosynthetic organisms having potential to treat the pollutant of industrial wastewater mainly by bioaccumulation and biosorption. They are able to accumulate organic and inorganic toxic substances, heavy metals, nutrients, pesticides in their cells/bodies from the wastewater. Algae can remove the excess nitrogen and phosphorus present in industrial wastewater through absorption. Nitrogen and phosphorus are commonly present in wastewaters which are essential components for the growth of algae. A wide range of algal species including *Chlamydomonas*, *Chlorella*, *Spirulina*, *Scenedesmus*, *Pediastrum*, *Cosmarium* and *Botryococcus* have been utilized for treatment of various industrial wastewaters (Table 1.4). These species are used to treat and remove color, odour, nitrogen, phosphorus, heavy metals, BOD, COD and other pollutants from various industrial wastewaters.

1.4.4 Plants

Removal of pollutants with the utilization of plants is known as phytoremediation. This strategy includes the use of plants that show high survivability in contaminated sites and the capacity to uptake pollutants, which prompts consequent evacuation of pollutants. Plants have been effectively used to remove heavy metal, petroleum hydrocarbons, pesticides, organic and inorganic contaminants and industrial by-products. Plant species with phytoremediation potential should have specific properties. They accumulate, extract, transform, degrade or volatilize contaminants at the levels that are toxic to ordinary plants and furthermore they have ability to remediate various pollutants at the same time. The phytoremediation process can take place by any of the following ways like phytoextraction, phytostabilization, phytovolatilization, phytodegradation, rhizofiltration. The pollutants enter the plant primarily through the roots by adsorption and accumulation. These pollutants might be stored in the roots, stems, or leaves; changed into less harmful chemicals inside the plant; or changed into gases that are released into the air as the plant transpires. There are several species of plants mainly aquatic plants known for their phytoremediation abilities to treat various industrial wastewaters such as *Acorus calamus*, *Typha latifolia*, *Typha domingensis*, *Cynodon dactylon* and *Phragmites communis* (Table 1.4).