



Recent Developments In Effluent Treatment Plants

Prof. K.. N. Tarkase¹, Shrutika. R. Gund², Ankita.M. Wadinkar³

Professor¹, Student², Student³

Department of Pharmaceutical Quality Assurance

Ahmednagar, India

Abstract

Effluent treatment plants (ETPs) are critical infrastructures aimed at reducing the environmental impacts of industrial wastewaters. Traditional methods, although effective to some extent, struggle with the complex and variable composition of modern effluents. Recent advancements in advanced oxidation processes, membrane technologies, nanotechnology applications, biotechnological innovations, and digital monitoring are paving the way toward more sustainable and efficient treatment systems. This review paper provides a comprehensive overview of these recent developments, their advantages and challenges, and highlights future prospects in the field of effluent treatment.

Keywords: Effluent, pollution, biological.

1. Introduction

Industrialization has greatly contributed to economic development but at the cost of environmental pollution, particularly water contamination. Effluents from industries such as textiles, pharmaceuticals, petrochemicals, and food processing often contain high loads of organic and inorganic pollutants.

Effluent treatment plants (ETPs) have been established to ensure that wastewater released into the environment meets regulatory standards. Traditional ETPs involve mechanical, chemical, and biological processes; however, the emerging complexity of pollutants demands advanced solutions.

Effluent Treatment Plant is a process of treating the industrial waste water or effluent rendering it safe for its reuse. It involves the Preliminary, Primary, Secondary and Tertiary treatment methods².

This review focuses on highlighting recent developments in effluent treatment technologies that aim to address these challenges more effectively.

1.1 Conventional Effluent Treatment Methods

Primary, secondary, and tertiary are the three broad stages of treatment. These are covered in detail below:

1. Primary Treatment

The first stage of treating wastewater is called primary treatment, and its main objective is to get rid of big particles and floating debris. Screening and removal of grit are the two primary therapy procedures. Large particles like rocks, plastics, and rags are removed from wastewater by filtering it through screens. Sand and gravel are examples of heavy inorganic particles that need to be settled in grit chambers or sedimentation tanks to prevent damage to downstream equipment.

2. Secondary Treatment

The main objectives of secondary treatment procedures are to eliminate suspended particles and organic materials from wastewater. Microorganisms play a crucial role in these processes by breaking down organic pollutants. Trickling filters and the activated sludge process are common secondary treatment techniques. In aeration tanks, wastewater is combined with a culture of microbial cells (activated sludge) to promote the biological breakdown of organic contaminants.

3. Tertiary Treatment

The next step, known as tertiary treatment, improves the wastewater's quality even more, especially for applications like water reuse or discharge into sensitive areas. Filtration, disinfection, and the removal of excess nutrients like phosphate and nitrogen are examples of tertiary treatment techniques. To get rid of any leftover suspended solids and tiny particles, methods like sand filters, multimedia filters, or membrane filtration (microfiltration, ultrafiltration) are used. The removal of pathogens and undesirable nutrients is achieved through chemical disinfection (chlorination, ozonation) or physical disinfection (UV irradiation), which guarantees the microbiological safety of treated wastewater. Using various methods, tertiary treatment is mostly used to purify water to make it safe to consume¹.

1.2 Recent Developments in Effluent Treatment

1.2.1 Advanced Oxidation Processes

For the oxidation of contaminants, AOPs rely on the in-situ generation of highly reactive hydroxyl radicals ($\cdot\text{OH}$) or other oxidative species. When introduced to water, these reactive species can oxidize almost any component in the water matrix, frequently at a reaction speed that is controlled by diffusion. As a result of $\cdot\text{OH}$'s unselective reaction, pollutants are rapidly and effectively broken down into tiny inorganic molecules. One or more main oxidants (such as oxygen, hydrogen peroxide, or ozone) and/or energy sources (such as UV radiation) or catalysts (such as titanium dioxide) can assist create hydroxyl radicals. To achieve a maximum $\cdot\text{OH}$ yield, precise, pre-programmed dosages, sequences, and combinations of these reagents are employed. AOPs have been dubbed the "water treatment processes of the 21st century" because, when used under well calibrated circumstances, they can generally lower the concentration of contaminants from several hundred parts per million to fewer than five parts per billion ².

When cleansing wastewater of biologically hazardous or non-biodegradable substances including volatile organic compounds, pesticides, petroleum components, and aromatics, the AOP process is especially

helpful. AOPs can also be utilized for tertiary treatment, which is the process of treating wastewater effluent from secondary treatment. The contaminating materials undergo mineralization, which is the process by which they are primarily transformed into stable inorganic compounds such as salts, carbon dioxide, and water. Reducing chemical pollutants and toxicity to a level that allows the cleansed wastewater to be reintroduced into receiving streams or, at the very least, into a traditional sewage treatment system is one of the objectives of wastewater purification using AOP processes³.

Although Fenton's reagent, an analytical reagent at the time, and other oxidation processes involving $\cdot\text{OH}$ have been around since the late 19th century, the use of these oxidative species in water treatment did not receive enough attention until 1987, when it was proposed that $\cdot\text{OH}$ could be generated "in sufficient quantity to affect water purification" and the term "Advanced Oxidation Processes" was first defined. Even now, AOPs are still not widely used in commerce, particularly in poor nations, primarily due to the comparatively high prices involved. Nonetheless, AOPs are a common method in tertiary treatment when the most stubborn organic and inorganic contaminants need to be removed due to their great oxidative capacity and effectiveness⁴.

The full-scale adoption of AOPs is currently being accelerated by growing interest in water reuse and stricter laws pertaining to water pollution. Currently, there are about 500 commercialized AOP installations worldwide, primarily in the US and Europe. Interest in AOPs is growing in other nations, such as China. Using improved catalyst and hydrogen peroxide formulations, the reaction, which uses H_2O_2 to generate $\cdot\text{OH}$, is conducted safely and effectively at low temperatures ($30\text{ }^\circ\text{C}$ to $50\text{ }^\circ\text{C}$) and in an acidic medium (pH 2.5 to 4.5)⁵.

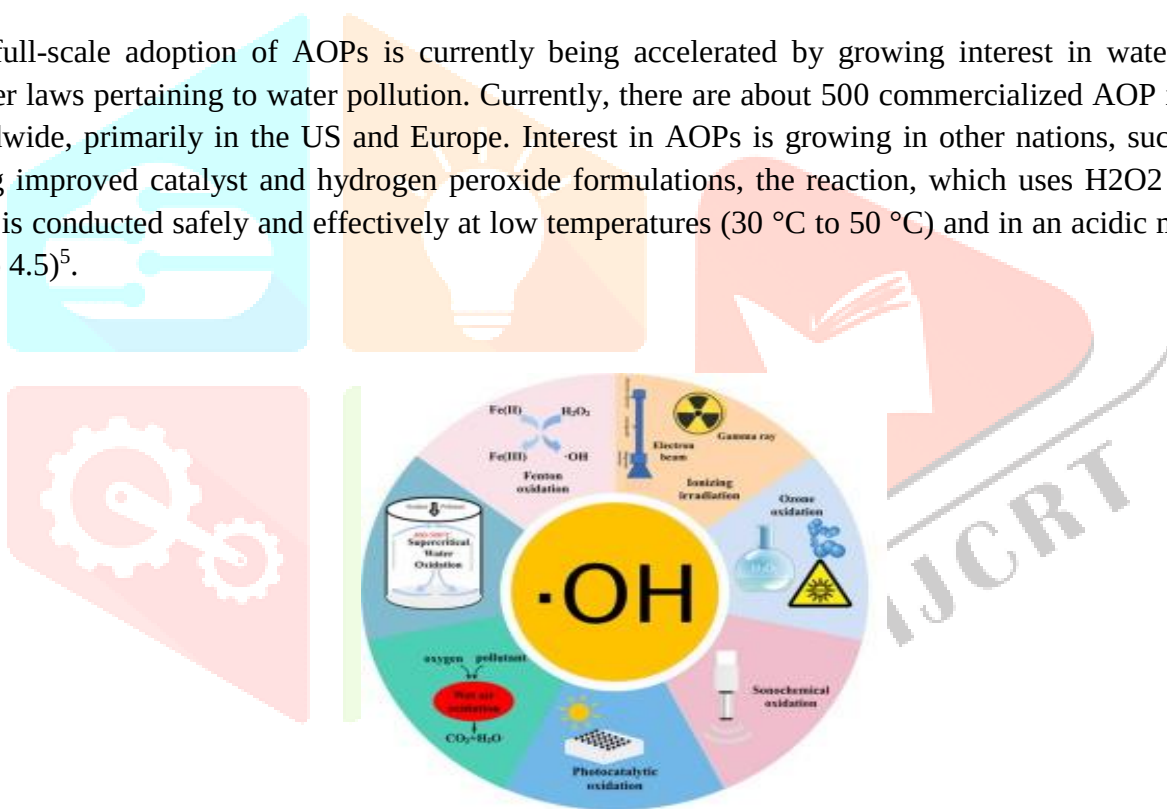


Fig 1. advanced oxidation process

1.2.2 Membrane Technologies

Compared to traditional thermal separation techniques like distillation, sublimation, or crystallization, membrane separation technologies need less energy because they don't require heating. Both the permeate and the retentate fractions can be acquired as usable products from the purely physical separation process. The food, biotechnology, and pharmaceutical sectors all make extensive use of membrane-based cold separation. Additionally, separations that could not be achieved with thermal separation techniques are made possible by the use of membranes. For instance, the components of azeotropic liquids or solutes that form isomorphous crystals cannot be separated by distillation or recrystallization; however, membrane technology can accomplish such separations. Certain individual chemicals or mixtures of substances can be selectively separated depending on the type of membrane. Reverse osmosis is a significant technical

application for producing drinking water. Membrane technology is becoming more and more significant in waste water treatment. Colloids and macromolecules can be effectively removed from wastewater using ultra/microfiltration. This is necessary if wastewater is released into delicate waters, particularly those used for recreational and contact water sports⁷.

Membrane operations

- Pressure-driven operations
 - Microfiltration
 - Ultrafiltration
 - Nanofiltration
 - Reverse osmosis
 - Gas separation
- Concentration driven operations
 - dialysis
 - pervaporation
 - forward osmosis
 - artificial lung
- Operations in an electric potential gradient
 - electrodialysis
 - membrane electrolysis e.g. chloroalkaline process
 - electro filtration
 - Fuel cell
- Operations in a temperature gradient

1.2.3 Membrane distillation

In the separation sector, membrane separation techniques are crucial. However, they weren't regarded as technically significant until the middle of the 1970s. The size of the separated particles and the separation methods determine the differences in membrane separation procedures⁸. Microfiltration, ultrafiltration, nanofiltration, reverse osmosis, electrolysis, dialysis, electrodialysis, gas separation, vapor permeation, pervaporation, membrane distillation, and membrane contactors are some of the commonly utilized membrane processes. No phase change occurs during any of the processes other than pervaporation. Every procedure is pressure-driven, with the exception of electrodialysis. Food and beverage processing (beer microfiltration, apple juice ultrafiltration), biotechnological applications, the pharmaceutical industry (antibiotic production, protein purification), water purification and wastewater treatment, the microelectronics industry, and other fields all make extensive use of microfiltration and ultrafiltration. Water treatment is the primary use for reverse osmosis membranes and nanofiltration. Dense membranes are used in membrane distillation and occasionally for gas separations, such as the extraction of CO₂ from

natural gas, N₂ from air, and organic vapor from air or a nitrogen stream. The latter procedure lowers the expenses of distillation procedures by aiding in the separation of azeotropic compositions⁹.

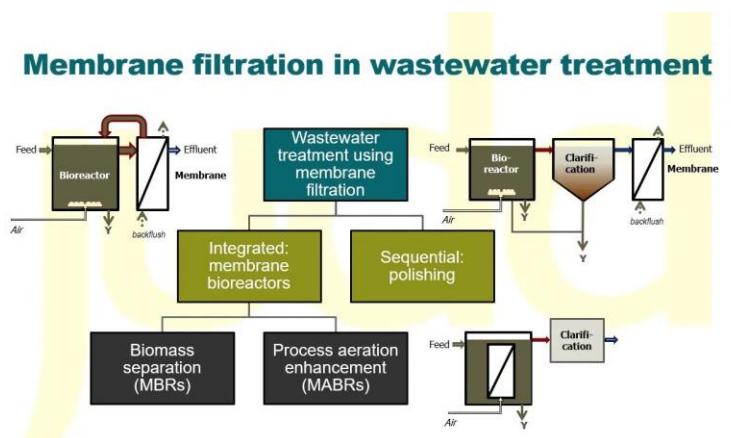


Fig 2. Membrane distillation process

1.2.3 Nanotechnology

Nowadays, water filtration methods heavily rely on nanotechnology. The manipulation of atoms at the nanoscale is known as nanotechnology. In the field of nanotechnology, nanomembranes are employed to remove physical, biological, and chemical pollutants from water and soften it. There are numerous methods in nanotechnology that employ nanoparticles to produce highly effective and safe drinking water. A few of these methods are now marketed¹⁰.

Nanotechnology is favored for improved water purification or treatment procedures. Water treatment procedures employ a wide variety of nanomaterials and nanoparticles. Water treatment, filtration, purification, desalination, and remediation can all benefit from nanotechnology.

The primary characteristics that make nanoparticles useful for treating water are:

- Greater surface area
- Smaller volume
- Stronger, more stable, and longer-lasting particles
- Materials may alter electrical, optical, physical, chemical, or biological properties at the nanoscale
- Facilitates chemical and biological reactions

The LifeSaver bottle, Lifesaver Jerrycan, Lifesaver Cube, Nanoceram, and NanoH₂O are examples of contemporary commercial water purifiers that use nanotechnology¹¹.

Excellent surface area and excellent material strength are combined in this sustainable material based on nanocellulose. It has a flexible hydrophilic surface chemistry and is chemically inert. Because of these characteristics, they are a very promising nanomaterial for use as a filter and membrane in water purification systems to eliminate chemical and bacterial pollutants from contaminated water. Nanocellulose is known to have a lot of promise for water filtration technology. Cellulose nanocrystals (CNC) and cellulose nanofibrils

(CNF) are two of the various forms of nanocellulose materials that are available for use in water purification systems. These are rod-shaped nanomaterials with diameters ranging from 2 to 20 nm and sizes between 100 and 2000 nm. These dimensions are mostly determined by the place of origin and the method of preparation used to create nanocellulose. These nanocellulose materials are used to eliminate organic contaminants from water, including colors, oils, and pesticide residues. Nowadays, sulfates, fluorides, and other organic chemicals are eliminated together with metal ions like Cu^{2+} , Fe^{2+} , and others by employing nanocellulose to create a totally biobased membrane. Compared to traditional filters, this bio-based nanocellulose filter offers greater benefits. Numerous techniques, including the hydrolysis of sulfuric acid and mechanical grinding, are used to prepare nanocellulose. The absorption principle is the foundation of most water filtration systems. The nanocellulose materials are functionalized with a positively charged cationic group to facilitate the absorption of anionic metal species. Likewise, the negatively charged anionic group functionalizes the nanocellulose material to facilitate the absorption of cationic metal species.

The cost and specificity of materials based on nanocellulose are limited for large-scale manufacture. In order to increase adsorption capacity, current research is based on the synthesis of hybrid nanocellulose material in conjunction with many additional nanomaterials¹².

1. Graphene coated nanofilter

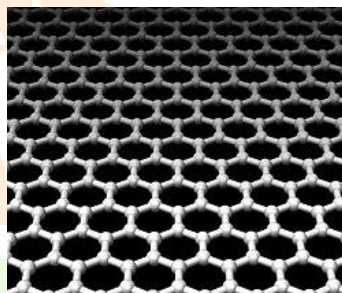


Fig.3 Graphene coated nanofilter

Graphene is physically robust, chemically dormant, and impermeable to liquids or gases. Therefore, carbon is essential to the creation of porous nanomaterials. It is possible to effectively segregate molecules in a gas or liquid phase using graphene membranes made of graphene oxide molecules or chemically modified graphene that is adhered using 2D nano-mediated arrays. Because of its special qualities, graphene-coated nanomembranes are thought to be more useful in water treatment. Vacuum filtering or covering graphene oxide solution as graphene oxide sheets yield graphene membranes. The water flow range was greater for the graphene-coated nanofiltration membrane. When used as nanofilters, graphene embedded with carbon nanotubes is more effective in removing salt ions, rejecting dyes from water effluent, and acting as an antifouling agent. Because graphene sheets and proteins have a strong connection, graphene nanofilter membranes have an efficient antifouling agent (12). Additionally, water dechlorination is aided by graphene oxide-coated nanofilter membranes. Furthermore, the most effective filter that might be sold commercially for water filtration is an ultrathin nanofilter coated with graphene. There are several types of graphene oxide membranes that can be employed, including free, surface-modified, and graphene-cast membranes for micro, nano, or ultrafilters. Because of the membrane's physiochemical characteristics and mechanical robustness, nanofilters are the most effective method for desalinating water. Additionally, creating and using graphene oxide-based nanofilters for water desalination has certain difficulties. The difficulties include surface imperfections, cost strategy, assembly, and mechanical instability if the nanofilters are nanosheets. Consequently, there are more areas in which research can be conducted for the benefit of society¹⁴.

2 Electrochemical Carbon nanotube filter

The application of carbon nanotubes as a water and wastewater filter has drawn a lot of interest. Since 1990, the mechanical, electrical, and chemical characteristics of carbon nanotubes have made them special and a prime option for study. The most effective technique for purifying water and wastewater was found to be the combination of carbon nanotubes with electrochemistry¹⁵. Electrochemistry aids in lowering the CNT's fouling rate. When compared to unmodified CNT-based filters, the energy reduction from electrochemistry-modified CNT-based ultra-filters is double. Thus, significant research in electrochemistry and nanotechnology has led to the development of electrochemical carbon nanotubes. Here, the CNT's electrochemical activity is utilized. In 1996, the first electrochemical CNT was created, and the outcomes were initially acknowledged¹⁶.

An electrochemical CNT filter is made up of electrodes and CNT in a methodical arrangement that allows the electrodes to draw in waste materials that clog the CNT according to its charges. This results in high filtering efficiency and prolongs the CNT's lifespan. Amino group-based colors can be readily removed from wastewater using electrochemical carbon nanotubes. Wastewater can usually be filtered and recycled using these electrochemical CNTs. There are currently a number of unreported developments in CNT-based electrochemical sensors that are being extensively studied in order to expand their use in biomedical systems¹⁷.

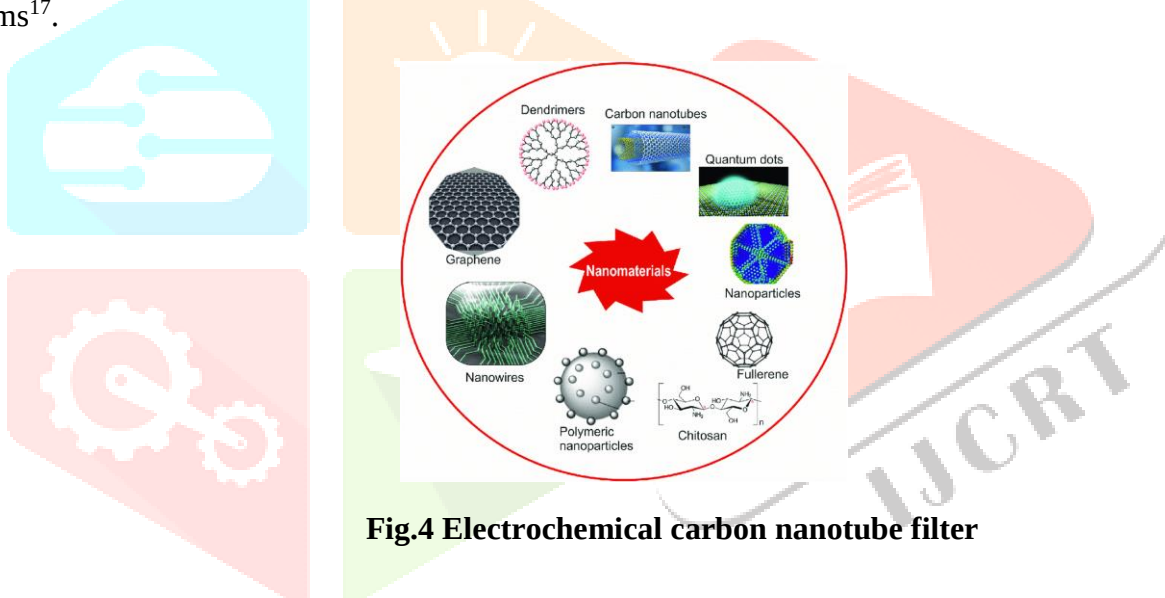


Fig.4 Electrochemical carbon nanotube filter

1.3 Aerobic treatment system

Similar to a septic tank system, an aerobic treatment system (ATS), sometimes known as an aerobic septic system, is a small-scale sewage treatment system that uses an aerobic process for digestion as opposed to merely the anaerobic process seen in septic systems. These systems can serve a single home or a small collection of homes and are frequently seen in rural locations without access to public sewers¹⁸. The aerobic treatment system, in contrast to the conventional septic system, generates a high-quality secondary effluent that is suitable for surface irrigation after sterilization. This reduces the necessary leach field area by up to half and gives much more freedom in the leach field's placement¹⁹.

1.3.1 Process

The following steps typically make up the ATS process:

- The pre-treatment phase, which eliminates big particles and other unwanted materials.
- The stage of aeration, during which aerobic microorganisms break down biological waste.

Undigested solids might settle during the settling stage. This results in the formation of a sludge that needs to be periodically eliminated from the system.

- The disinfecting step, which creates an antiseptic output by mixing chlorine or a comparable disinfectant with the water. An alternative is UV disinfection, which involves exposing the water to UV light within a UV disinfection unit.

When a sterile effluent is needed, like in situations where the effluent is dispersed above ground, the optional disinfection stage is employed. Calcium hypochlorite pills, specifically designed for waste treatment systems, are commonly used as disinfectants. The pills are designed to decompose rapidly in the presence of sunshine. Plants in the leach field may be killed by stabilized forms of chlorine, which remain after the effluent has been distributed²⁰.

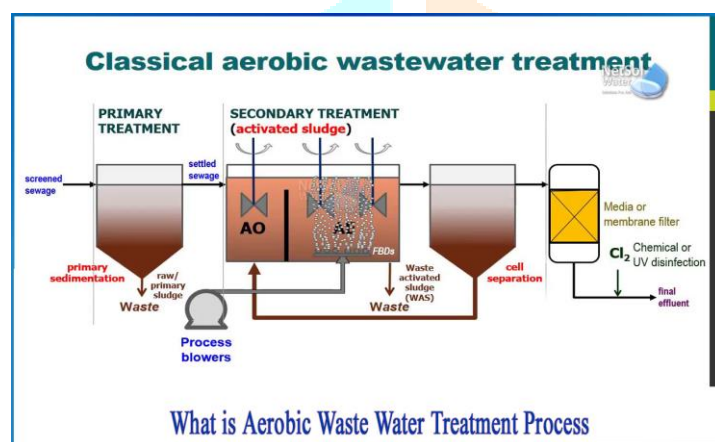


Fig.5 Aerobic treatment system

1.4 Decentralized wastewater system

Wastewater from tiny, low-density towns, isolated homes and buildings, and individual public or private properties is transported, treated, and disposed of or reused via decentralized wastewater systems, also known as decentralized wastewater treatment systems. When a suitable water source is available inside or near buildings, wastewater flow is produced²¹. Relatively close to the effluent's source of generation, decentralized wastewater systems treat, reuse, or dispose of it. By significantly lowering health and environmental risks, they aim to safeguard both the environment and public health. They are also known as "decentralized wastewater treatment systems" due to the fact that selecting an appropriate treatment and/or disposal facility is the primary technical issue²².

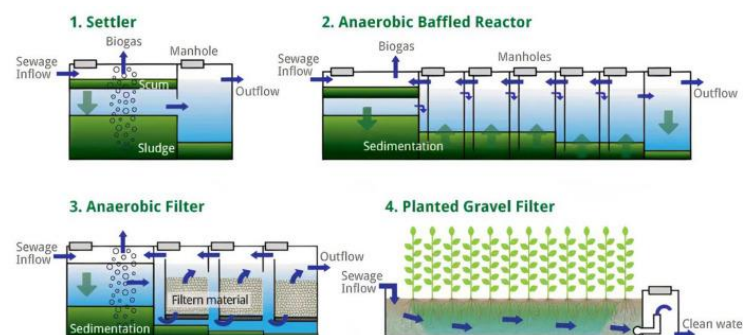


Fig.6 Decentralized wastewater system

1.5 Sewage Wastewater treatment

In order to prevent water pollution from raw sewage discharges, sewage treatment is a sort of wastewater treatment that tries to remove contaminants from sewage to generate an effluent that is suitable to discharge to the surrounding environment or an intended reuse application. Sewage may contain pre-treated industrial effluent in addition to wastewater from homes and businesses. There are many different sewage treatment methods available. These can be massive centralized systems that use a network of pipelines and pump stations (known as sewerage) to transport the sewage to a treatment facility, or they can be decentralized systems, such as on-site treatment systems. In cities with combined sewers, stormwater, or urban runoff, is also transported to the sewage treatment facility by the sewers. While sophisticated treatment also includes a tertiary treatment stage with polishing procedures and nutrient removal, sewage treatment typically consists of two basic phases, known as primary and secondary treatment. By employing aerobic or anaerobic biological processes, secondary treatment can lower the amount of organic matter (as indicated by biological oxygen demand) in sewage. For the elimination of organic micropollutants, including medications, a so-called quaternary treatment step (also known as advanced treatment) may be added. In Sweden, for instance, this has been fully implemented²³.

Numerous approaches for treating sewage have been developed, the majority of which use biological treatment processes. When selecting an appropriate technology, design engineers and decision makers must consider the technical and financial aspects of each option. Desired effluent quality, anticipated building and running costs, land availability, energy requirements, and sustainability considerations are frequently the primary selection reasons. Sewage is frequently handled by various on-site sanitation systems rather than being transported in sewers in developing nations and rural areas with low population density. These systems include vermifilter systems, on-site sewage systems (OSS), septic tanks that are connected to drain fields, and many more.

Conversely, sophisticated and comparatively costly sewage treatment facilities could incorporate a fourth stage of treatment to eliminate micropollutants, along with tertiary treatment that includes disinfection.

An estimated 52% of sewage worldwide is treated. However, the rates at which sewage is treated vary greatly among nations worldwide. For instance, developing nations typically handle only 4.2% of their sewage, compared to 74% in high-income nations. Sewage treatment falls under the category of sanitation. Along with solid and human waste management, sanitation also involves stormwater (drainage) management. The terms "sewage treatment plant" and "sewage treatment plant" are frequently used interchangeably²⁴.

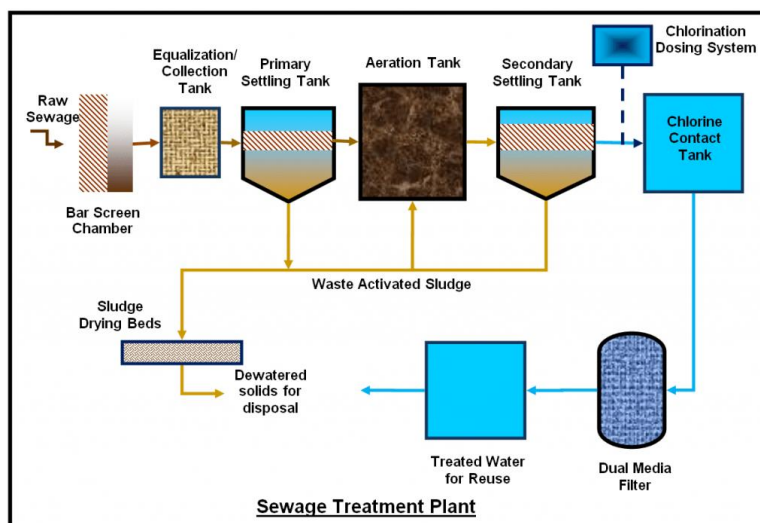


Fig.7 Sewage Wastewater treatment

1.5.1 API oil–water separator

The purpose of an API oil–water separator is to remove large quantities of oil and suspended solids from industrial wastewater generated in petrochemical, chemical, natural gas processing, and oil refinery facilities, among other sources of industrial oily water²⁵. The API separator is a gravity separation device that defines the rise velocity of oil droplets according to their size and density using Stokes Law. The specific gravity difference between wastewater and oil is the basis for the design because it is significantly less than the specific gravity difference between water and suspended particulates²⁶.

The oil rises to the top of the separator, the suspended solids settle as a sediment layer at the bottom, and the cleaned wastewater forms the intermediate layer between the solids and the oil layer. The term comes from the fact that these separators are made in accordance with American Petroleum Institute (API) specifications²⁷.

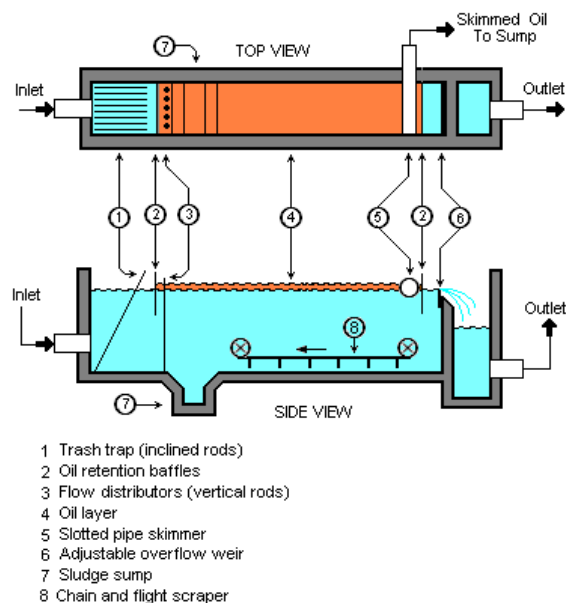


Fig.8 API oil–water separator

1.5.2 Upflow anaerobic sludge blanket digestion

One type of anaerobic digester utilized for wastewater treatment is the upflow anaerobic sludge blanket (UASB) technology, often known as the UASB reactor. UASB creates a covering of granular sludge that floats in the tank using an anaerobic process. Anaerobic bacteria digest (degrade) wastewater as it passes upward through the blanket. With the help of flocculants, the blanket is suspended by the upward flow and the settling action of gravity. Around three months is when the blanket starts to mature. Bacterial aggregations cover the surface of the tiny sludge particles that start to form. The flow circumstances produce a selective environment where only bacteria that can adhere to one another survive and multiply in the absence of any support matrix. The aggregates eventually come together to create "granules," which are dense, compact biofilms²⁸.

As a by-product, biogas with a high methane content can be recovered and used as an energy source to cover its own operating costs and produce electricity for export. When using the technique, it must be continuously monitored to make sure the sludge blanket is maintained and not washed out, which would negate its effectiveness. The digestion tanks can be heated again using the heat generated as a byproduct of the production of power²⁹.

A dual solid and hydraulic (liquid) retention time in the digesters is made possible by the blanketing of the sludge. For up to 90 days, solids that need a high level of digestion can stay in the reactors. In the liquid phase, sugars dissolved in the liquid waste stream can be swiftly transformed into gas, which can leave the system in less than a day.

Waste water streams may usually be diluted using UASB reactors³⁰.

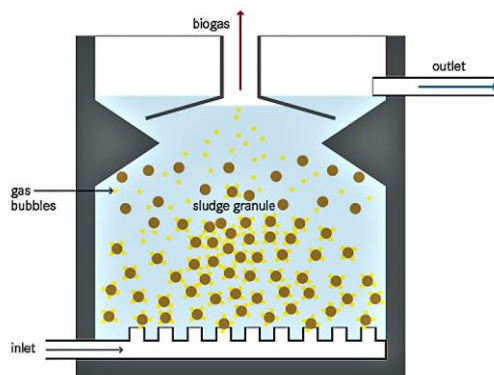


Fig.9 Upflow anaerobic sludge blanket digestion

2. Methods of CETP:

2.1 Coagulation and Flocculation:

This is the major method used for the treatment of industrial waste water. The compound aluminium sulphate was used by the Egyptians so as to treat the contaminated water by settling the contaminants in the water³¹.

2.2 Adsorption and Bioadsorption:

Adsorption is a exothermic process in which a molecule or i.e adsorbate is transferred onto a solid by a physiochemical or chemical interaction. Biosorption is a type of adsorption in which the bacteria, algae or fungi are used as adsorbents due to their ability to bind to heavy metals by various spontaneous Physiochemical pathways.

2.3 Carbon-based Nano-adsorbents:

There are different allotropes of nanostructures of carbon like activated carbon, carbon nanotubes, buckyballs T ,graphite and graphene³². CNTS

shows higher adsorption of organic chemicals than the activated carbon due to its larger Surface area and contaminant - CNT interactions. Various Polar organic compounds are adsorb strongly adsorbed by CNT³³.

2.4 Polymer based Nanoparticles:

These include polysaccharides, Cyclodextrin covalent organic polymers, etclignininderieved nanomaterials have been used for wastewater treatment They are used for the catalytic degradation of dyes, nitrearenes and heavy metals³².

2.5 Membrane bioreactor :

Membrane bioreactor is the process that uses both biological treatment along with membrane technology for the treatment of wastewater. The performance of MBR Varies with the activity of microorganisms In two different ways, quality of effluent and the efficient ability of MBP to treat the Waste Water³⁴. MBR can be used in anaerobic treatments Other than Conventional anaerobic treatments Ty which requires needs. produces high quality effluent³⁵.

2.6 Sequencing batch record:

SBP technology Works on a fill and draw type biological Waste Water treatment. It involves single or multiple tanks using less EOD COD biological treatment, etc³⁶. Various factors like influent waste water, environmental and operational factors influence the performance of SBR. Many other factors like cycle time. Sludge retention time, aeration rate, etc also influence the performance of SBR³⁷.

2.7 Moving bed biofilm reactor:

MBBR is the process in which the biofilm is supported by carriers, the biofilms distributed throughout the reactor Which enhances the residence time for microorganisms that improves the removal of waste water. MBBR is a efficient system that removes organic compounds, nutrients, etc³⁸.

2.8 Electrocoagulation:

Electrocoagulation is a process in which the organic compounds are degraded. or coagulated. The organic compounds coagulate and the aggregation of colloidal particles enhance the removal of waste from the water The Organic compound such as citrate, Ethylenediaminetetracetic acid (EDTA), tartrate, HA form chelates with heavy metals which results in theresistant complexes formation that removes the waste³⁹. The electrocoagulation set up contains electrolytic cell, metal electrodes and a DC power source⁴⁰.

2.9 Bioremediation:

Bioremediation is a process in which and are used bacteria, algae, fungi and yeast are used to remove contaminants from the water. The contaminants like heavy metals are converted to non-toxic compounds by the water and carbon dioxide are formed⁴¹.

3. Biotechnological Innovations

Biological treatment systems are evolving with the use of genetically engineered microorganisms (GEMs) and enzyme-based degradation techniques.

Bioaugmentation strategies, involving the addition of specialized microbial strains, have improved biodegradation rates for complex pollutants such as phenols and hydrocarbons .

Enzymatic treatments, particularly using laccases and peroxidases, provide eco-friendly alternatives for the degradation of textile dyes and phenolic wastewaters .

However, the scalability and stability of such biological systems under industrial conditions remain areas of ongoing research.(30)

4. Digitalization and Smart Monitoring

Digitalization through IOT (Internet of Things), AI (Artificial Intelligence), and big data analytics is transforming ETP operations.

Real-time monitoring sensors for pH, dissolved oxygen, turbidity, and chemical oxygen demand (COD) are improving operational control

Predictive maintenance powered by machine learning models reduces downtime and enhances the reliability of treatment processes

Blockchain is also being explored for transparent water quality monitoring and regulatory compliance documentation (31).

5. Case Studies

In India, the integration of a membrane bioreactor (MBR) and ozonation in textile industry ETPs resulted in 95% chemical oxygen demand (COD) reduction (32)

A pharmaceutical company in Europe implemented an advanced oxidation and biological treatment hybrid system achieving over 80% removal of micro-pollutants

Chinese thermal power plants successfully adopted Zero Liquid Discharge (ZLD) systems to recover over 90% of wastewater along with by-products such as salts.(33)

6. Challenges in Recent ETP Technologies

High capital and operational costs limit the widespread adoption of advanced ETP technologies

Energy-intensive nature of processes such as AOPs and ZLD poses sustainability concerns

Management of secondary waste products (e.g., sludge, concentrates) remains a pressing issue

Lack of trained personnel and awareness hinders the operation and maintenance of sophisticated systems

Policy and regulatory frameworks need to evolve to support innovative and decentralized solutions (34)

7. Future Prospects

Future research should focus on low-energy treatment technologies, such as bioelectrochemical systems and solar-driven AOPs.

Nanomaterials derived from natural and biodegradable sources are gaining interest to minimize environmental risks.(35)

Resource recovery from wastewater, such as nutrients, energy, and potable water, will align ETPs with circular economy principles

Decentralized modular ETP units could provide tailored solutions for small industries and remote areas (36)

8. Conclusion

Recent advancements in effluent treatment technologies demonstrate the shift toward more sustainable, efficient, and resilient systems .

Innovations in oxidation, membranes, nanomaterials, biotechnology, and digital monitoring are enabling ETPs to meet increasingly stringent discharge standards Continued interdisciplinary collaboration among engineers, scientists, policymakers, and industries is essential to overcome existing challenges and achieve long-term water sustainability goals .

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