NATIONAL ENVIRONMENTAL SCIENCE ACADEMY (NESA)

International Journal on Agricultural Sciences
http://nesa-india.org | http://journal.nesa-india.org/index/IJAS
IJAS 16(1): 17-32 **(2025)** • ISSN: 0976-450X
https://doi.org/10.53390/IJAS.2025.16103

WASTEWATER MANAGEMENT STRATEGIES WITH SPECIAL REFERENCE TO AGRICULTURAL RUNOFF

Ashish Tiwari[1] and Anurag Tiwari[2]*

[1]Department of Chemistry, Govt. College Dumariya, Jarhi, Surajpur, Chhattisgarh, India.
[2]Department of Applied Mechanics, Motilal Nehru National Institute of Technology Allahabad, Prayagraj-211004, Uttar Pradesh, India.

Review Paper

Received: **16.01.2025** Revised: **08.02.2025** Accepted: **26.02.2025**

ABSTRACT

Agricultural wastewater, which is produced by livestock operations, agro-industrial processes, and irrigation runoff, presents serious environmental problems since it contains pesticides, organic matter, and nutrients. In order to avoid water pollution and guarantee sustainable farming methods, effective treatment is necessary. This essay examines the different approaches used to treat wastewater, paying particular attention to supplies from agriculture. Advanced approaches including membrane filtration, engineered wetlands, anaerobic digestion, and bioremediation are presented alongside more traditional ones like primary sedimentation, secondary biological treatment, and tertiary nutrient removal. The focus is on economical and environmentally friendly solutions that are appropriate for farming and rural areas. A technique to treating agricultural wastewater that shows promise is the combination of natural treatment systems and contemporary technologies. Issues like the necessity for farmer knowledge and the variation in waste content are also covered. According to the study's findings, a mix of suitable treatment techniques can improve water reuse and support sustainable farming.

No. of Pages: 16 **References: 74**

Keywords: Agricultural wastewater, constructed wetlands, bioremediation, anaerobic digestion, nutrient removal, sustainable agriculture, membrane filtration,

INTRODUCTION

Water pollution is an escalating global concern that affects both developed and developing nations. Major contributors include urbanization, industrialization, and particularly, agriculture. It is estimated that nearly 80 percent of global municipal wastewater is discharged into water bodies without adequate treatment, and industries contribute millions of tons of heavy metals, solvents, sludge, and other pollutants each year (WWAP, 2024).

In the Indian context, the growing use of veterinary medicines—such as antibiotics, growth hormones, and vaccines—in livestock and aquaculture has emerged as a significant environmental hazard. These substances often enter aquatic ecosystems through surface runoff or leaching, contributing to the rise of antimicrobial resistance (AMR). In response, the Food Safety and Standards Authority of India (FSSAI) in 2024 imposed restrictions on certain antibiotics used in meat, milk, poultry, and aquaculture. This policy reflects increasing awareness of the pathways through which agricultural practices influence waterborne contaminants and subsequently human and ecosystem health.

Globally, agricultural pollution remains a leading cause of deteriorating water quality. Despite improvements in awareness and regulation, agricultural practices continue to contribute disproportionately to water degradation. The widespread use of synthetic fertilizers and pesticides has led to excessive nutrient loading, particularly nitrogen and phosphorus, which are recognized as

*Corresponding author: *tiwari.anuniit93@gmail.com*

major drivers of eutrophication in aquatic ecosystems (Gao et al., 2022; Zhang et al., 2021).

The issue is compounded in developing countries by insufficient wastewater treatment infrastructure. Agricultural runoff often mixes with untreated urban wastewater, creating a complex cocktail of pollutants that contaminate surface and groundwater systems (Kumar et al., 2023). The intensification of livestock and crop production has increased the discharge of nutrient-rich waste into the environment, further contributing to both chemical and microbiological pollution (Singh et al., 2020).

Veterinary pharmaceuticals are now recognized as an emerging class of contaminants. These compounds, particularly antibiotics and hormones, have been found to leach into nearby water bodies, potentially disrupting endocrine systems and fostering resistant bacterial strains (Li et al., 2021). These substances have been detected in alarming concentrations in drinking water sources and groundwater near farms (Chen et al., 2024).

Climate change is exacerbating these effects. Variability in rainfall and rising temperatures are affecting nutrient cycling, leading to sporadic pollution events such as algal blooms that cause oxygen depletion and biodiversity loss (Wang et al., 2022).

To mitigate such effects, researchers have advocated for the adoption of nature-based solutions and precision agriculture technologies. These include controlled fertilizer application using AI and sensors, as well as ecological buffers like constructed wetlands and vegetative strips that help trap nutrients and sediments (Ahmed et al., 2023; Fernández et al., 2020). Such strategies aim to reduce non-point source pollution, which remains difficult to control with conventional regulations.

Wastewater reuse and sustainable treatment methods are gaining traction as essential solutions to the twin challenges of water scarcity and pollution. Alagha et al. (2020) demonstrated that sequencing batch reactors (SBRs) are effective under varied anoxic conditions, supporting their application in water reuse. Villarín and Merel (2020) suggested a shift toward decentralized treatment systems and circular economy models. Tortajada (2020) emphasized that properly treated wastewater can help meet Sustainable Development Goals, particularly clean water and sanitation.

In India, Kamble et al. (2019) conducted life cycle assessments of municipal treatment plants, revealing trade-offs between environmental performance and economic feasibility. Fito and Van Hulle (2021) emphasized the importance of robust treatment in ensuring the safe reuse of wastewater in agriculture. Baskar et al. (2022) highlighted the need to manage spent adsorbents through regeneration and recovery, while Chojnacka et al. (2020) promoted fertigation using reclaimed water as a sustainable but technically challenging practice.

While high-income countries have made strides through stricter regulations and technological innovation, many low- and middle-income countries struggle with enforcement, funding, and infrastructure limitations. This underscores the importance of global knowledge-sharing and collaborative frameworks to address the cross-border nature of agricultural water pollution (UNEP, 2021).

Agriculture accounts for nearly 70 percent of freshwater withdrawals worldwide, making it a significant contributor to water pollution. Farms discharge large volumes of agrochemicals, organic matter, sediment, veterinary residues, and saline runoff into water systems (UNEP, 2016). In many regions, agricultural pollution has overtaken industrial and urban waste as the leading source of inland and coastal water contamination. Nitrate pollution from fertilizers, in particular, is the most widespread groundwater contaminant globally (WWAP, 2013).

Regional data reinforce this trend. In the European Union, 38 percent of water bodies are under significant pressure from agricultural pollution (WWAP, 2015). In the United States, agriculture is the primary pollution source in rivers and streams and ranks second and third in wetlands and lakes, respectively (US EPA, 2016). In China, agriculture is the main contributor to both surface and groundwater nitrogen pollution (FAO, 2013).

The pressures from agriculture stem from cropping, livestock, and aquaculture systems, all of which have expanded rapidly to meet growing food demand. Irrigated farmland has doubled in recent decades (FAO, 2014), and global livestock numbers rose from 7.3 billion units in 1970 to 24.2 billion in 2011 (FAO, 2016a). Aquaculture has increased over twentyfold since the 1980s, particularly in Asia (FAO, 2016b). This growth has been fueled by intensified use of chemical inputs, land expansion, and irrigation—all of which have increased the risk of pollution.

The livestock sector, in particular, poses serious water quality challenges. Manure and urine discharge contribute high loads of nitrogen, phosphorus, and pathogens to water systems (FAO, 2006). In addition, a new class of pollutants—veterinary drugs such as antibiotics and hormones—has emerged, with serious implications for environmental and public health. These contaminants, along with zoonotic pathogens, pose risks to drinking water quality and aquatic ecosystems (WHO, 2012).

The health consequences of agricultural water pollution are well-documented. High nitrate levels in drinking water can cause methemoglobinemia or "blue baby syndrome," which is potentially fatal in infants. Persistent pesticides, such as DDT and organophosphates, though banned in many regions, continue to be used in poorer countries and pose risks of acute and chronic toxicity. Ecosystem damage includes eutrophication, fish kills, and biodiversity loss. The economic cost is substantial—OECD countries alone incur billions of dollars annually in environmental and social damages from agricultural water pollution (OECD, 2012a).

There is a need for comprehensive, region-specific databases on pollutant loads from agriculture, especially in the Global South, to support targeted interventions.

- Limited surveillance of veterinary pharmaceuticals, hormone residues, and AMR pathogens in water sources restricts risk assessments and policy response.
- While advanced treatment and monitoring technologies exist, their implementation is constrained by weak regulatory frameworks, particularly in low-income countries.
- Although shown to be effective, ecological buffers, wetlands, and agroforestry are underutilized due to land and incentive constraints.
- Many smallholder farmers lack access to training in precision farming, waste management, and safe chemical use.
- Strategies to reduce runoff and leaching under changing climate conditions remain inadequately developed and poorly integrated into agricultural planning.

1. Agricultural Pollution

Biological and abiotic results of farming operations that harm people and their financial interests, or contaminate or degrade the environment and nearby ecosystems, are referred to as agricultural pollution. There are several possible sources of the contamination, including more diffuse, landscape-level sources (sometimes referred to as non-point source pollution) and point source water pollution (originating from a single discharge point).

The quantity and effects of these contaminants are greatly influenced by management techniques. Management strategies cover everything from housing and animal care to the application of fertilizers and pesticides in international farming operations.

Table 1: Outlines of various pollutant categories along with representative indicators.

Pollutant Category	Pollutant Category	Pollutant Category
Nutrients	Animal excrement and chemical and organic fertilizers both contain nitrogen and phosphorus, which are typically found in water as nitrate, ammonia, or phosphate.	Crops, Livestock
Pesticides	Herbicides, insecticides, fungicides, and bactericides, such as carbamates, pyrethroids, organophosphates, and organochlorine pesticides, among others (many, like DDT, are prohibited in most countries but are nonetheless used illegally and persistently; examples include	Crops
Salts	Sodium, chloride, potassium, magnesium, sulfate, calcium, and bicarbonate ions, for instance. This can be measured in water either directly as total dissolved solids or indirectly as electric conductivity.	Crops, Livestock
Sediment	Measured in water as nephelometric turbidity units or total suspended particles, particularly from pond drainage during harvesting	Crops, Livestock

Organic matter	Organic compounds like plant matter and animal feces are examples of chemical or biological oxygen-demanding substances that, during their degradation, deplete the dissolved oxygen in water.	Livestock, Aquaculture
Pathogens	indications of bacteria and pathogens, such as enterococci, fecal coliforms, total coliforms, and Escherichia coli.	Livestock
Metals	e.g., selenium, lead, copper, mercury, arsenic, and manganese	Crops, Livestock, Aquaculture
Emerging pollutants	e.g., drug residues, hormones, and feed additives	Crops, Livestock, Aquaculture

1. Sources of Agricultural Pollution

3.1 Abiotic Sources

fertilizers, pesticides, Fluoride, Cadmium, radioactive substances, additional metals, runoff from leaching and eutrophication, organic pollutants, Metals that are heavy

3.1.1 Pesticides

To manage pests that interfere with crop production, agricultural land is treated with pesticides and herbicides. Pesticides can change microbial processes, boost plant uptake of the chemical, and be poisonous to soil organisms, all of which can lead to soil pollution. The compound's distinct chemistry determines how long the pesticides and herbicides last since it influences sorption dynamics and the subsequent fate and transport in the soil environment. Animals that consume infected bugs and soil organisms may also collect pesticides. Furthermore, natural enemies of pests—that is, insects that feed on or parasitize pests—and helpful insects like pollinators may suffer greater damage from pesticides than the actual pests.

Fig 1: Aerial application of Pesticides.

When pesticides combine with water and permeate the soil, they can contaminate groundwater. This process is known as pesticide leaching. The degree of rainfall and irrigation, as well as the properties of the soil and pesticides, are related to the quantity of leaching. Leaching is more likely to occur when a water-soluble pesticide is used, when the soil has a sandy texture, when extensive watering takes place shortly after the pesticide is applied, or when the pesticide's adsorption capacity to the soil is poor. In addition to treated fields, leaching can also come from places where pesticides are mixed, where equipment used to apply them is washed, or where they are disposed of.

3.1.1 Fertilizers

Produce and other plant matter are produced with a very small percentage of nitrogen-based fertilizers. The rest is lost as runoff or builds up in the soil. The high water solubility of nitrate and the high rates of nitrogen-containing fertilizer application result in increased runoff into surface water and groundwater leaching, which pollutes groundwater. Overuse of nitrogen-containing fertilizers, whether natural or manufactured, is especially harmful because a large portion of the nitrogen that plants cannot absorb is converted to easily leached nitrate.

"Blue baby syndrome" (acquired methemoglobinemia) can be brought on by groundwater containing nitrate levels more than 10 mg/L (10 ppm). If fertilizer nutrients—particularly nitrates—leach through soil into groundwater or are carried off soil into watercourses, they can harm both human health and natural environments. Furthermore, improper fertilizer application resulted in ammonia pollution of the air.

3.1.2 Cadmium

Cadmium levels in fertilizers that contain phosphorus vary widely and can be harmful. For instance, the amount of cadmium in mono-ammonium phosphate fertilizer can range from 0.14 mg/kg to 50.9 mg/kg. This is due to the fact that the phosphate rock that is used to make them can have a cadmium content of up to 188 mg/kg (for instance, deposits in the Christmas islands and Nauru). High-cadmium fertilizer used continuously might contaminate plants and soil. The European Commission has examined limiting the amount of cadmium in phosphate fertilizers. The cadmium level is currently used by manufacturers of fertilizers that contain phosphorus to choose phosphate rock.

3.1.3 Fluoride

Fluoride concentrations in phosphate rocks are high. As a result, soil fluoride concentrations have increased due to the extensive use of phosphate fertilizers. It has been discovered that the likelihood of fluoride toxicity to livestock that consume polluted soils is more concerning than fertilizer-induced food contamination because plants do not acquire much fluoride from the soil. Fluoride's effects on soil microbes may also be a cause for concern.

3.1.4 Radioactive elements

Both the fertilizer production process and the amounts of radioactive elements in the parent material affect the fertilizers' radioactive content, which varies widely. The quantities of uranium-238 in phosphate rock can vary from 7 to 100 pCi/g, while those in phosphate fertilizers can range from 1 to 67 pCi/g. Concentrations of uranium-238 in soils and drainage waters can be many times higher than normal when large annual rates of phosphorus fertilizer are applied. Nevertheless, these increases have very little effect (less than 0.05 mSv/y) on the danger to human health from food contamination by radinuclides.

3.1.5 Other metals

Lead, arsenic, cadmium, chromium, and nickel are among the hazardous metals found in steel industry wastes that are recycled into fertilizers due to their high zinc content, which is necessary for plant growth. Mercury, lead, and arsenic are the most prevalent harmful substances found in this kind of fertilizer. It is possible to eliminate these potentially dangerous contaminants, but doing so comes at a hefty expense. Although there are many highly pure fertilizers on the market, Miracle-Gro and other highly water-soluble fertilizers with blue dyes are probably the most well-known. The plant nursery industry uses these extremely water-soluble fertilizers, which are substantially less expensive in larger packages than in retail settings. Granular garden fertilizers prepared with high-quality ingredients are also available at low-cost retail stores.

3.1.6 Leaching, runoff, and eutrophication

Fig 2: Eutrofication.

Important plant nutrients can be obtained from the nitrogen (N) and phosphorus (P) that are supplied to agricultural land (via synthetic fertilizers, composts, manures, biosolids, etc.). Excess N and P, however, can have detrimental effects on the ecosystem if improperly controlled. Nitrate pollution of groundwater can result from an excess of nitrogen (N) provided by both synthetic fertilizers (as highly soluble nitrate) and organic sources such manures (whose organic N is converted to nitrate by soil microbes). Blue infant syndrome can be brought on by drinking water tainted with nitrate. In addition to surplus P from these same fertilizer sources, eutrophication can happen downstream as a result of an overabundance of nutrients, creating dead zones, which are anoxic places.

3.1.1 Organic contaminants

Numerous minerals included in manures and biosolids are used as food by both humans and animals. Recycling soil nutrients is made possible by the practice of reusing such waste materials on agricultural land. The problem is that in addition to nutrients like carbon, nitrogen, and phosphorus, manures and biosolids may also contain pollutants including personal care products (PPCPs) and medications.

Both people and animals eat a huge diversity of PPCPs, each of which has a distinct chemistry in both terrestrial and aquatic habitats. Because of this, not all have had their influence on the quality of the land, water, and air evaluated. To determine the amounts of different PPCPs present, the US Environmental Protection Agency (EPA) has analyzed sewage sludge from wastewater treatment facilities around the US.

3.1.2 Heavy metals

Fertilizers, organic wastes like manures, and industrial byproduct wastes are the main sources of heavy metals (such as lead, cadmium, arsenic, and mercury) in agricultural systems. Certain farming practices, including irrigation, can cause the naturally occurring selenium (Se) in the soil to build up. This may lead to selenium concentrations in downstream water reservoirs that are harmful to people, animals, and wildlife. Named after the Kesterson Reservoir in the San Joaquin Valley (California, USA), which was designated a toxic waste dump in 1987, this mechanism is called the "Kesterson Effect."

3.1.3 Soil erosion and sedimentation

Due to intense management or ineffective land cover, agriculture significantly contributes to soil erosion and sediment deposition. An estimated 6 million hectares of productive land experience an irreversible decline in fertility annually as a result of agricultural soil degradation. Water quality is impacted by sedimentation, or the buildup of sediments in runoff water, in a number of ways. The transport capacity of rivers, streams, ditches, and navigation channels can all be reduced by sedimentation. Additionally, it may reduce the amount of light that reaches the water, which could have an impact on aquatic biota. Fish eating patterns may be disrupted by the turbidity that results from sedimentation, which could have an impact on population dynamics. Additionally, sedimentation influences the movement and buildup of contaminants, such as phosphorus and other types of pesticides.

3.2 Biotic sources:

Agricultural activities generate both nonpoint and point source pollution, significantly affecting water quality and greenhouse gas emissions. Nonpoint sources such as sediment and nutrient runoff, along with pesticides, enter water bodies diffusely through rainfall or irrigation. Point sources, including animal waste, piggery discharge, and effluents from milking parlours, slaughterhouses, and vegetable washing, release concentrated pollutants. Effective manure management practices like composting, anaerobic digestion, and solid-liquid separation, alongside sustainable methods such as biopesticides and biological control, are essential to mitigate environmental risks and promote circular agriculture.

3.2.1 Greenhouse gases from fecal waste

According to the Food and Agriculture Organization (FAO) of the United Nations, cattle worldwide are directly or indirectly responsible for 18% of anthropogenic greenhouse gas emissions. According to this data, livestock emissions were higher than transportation-related emissions.

3.2.2 Biopesticides

Biopesticides are insecticides made from natural sources, such as plants, animals, microbes, and certain minerals. Because biopesticides are safe to handle, typically have a short residual period, and do not significantly harm beneficial invertebrates or vertebrates, they can be used as an alternative to conventional pesticides to minimize overall agricultural pollution. Although there are some worries that biopesticides can harm non-target species populations, the EPA regulates biopesticides in the US. The government doesn't need as much information to register the use of biopesticides because they are less dangerous and have less of an impact on the environment than other pesticides. According to the United States Department of Agriculture's National Organic Program guidelines for organic crop cultivation, a variety of biopesticides are allowed.

The establishment of these alien species may also be aided by ecological disturbances brought on by farming activities. Weeds may also spread as a result of contaminated equipment, animals, and feed, as well as infected crop or pasture seed.

3.2.3 Manure treatment:

Composting: It is a solid manure management technique that uses either the solids from a liquid manure separator or solid manure from bedded pack pens. Composting can be done in two ways: actively and passively. Active composting involves periodic churning of the manure, while passive composting does not. Because of partial breakdown and reduced gas diffusion rates, passive composting has been shown to have fewer greenhouse gas emissions.

Solid-liquid separation: For simpler management, manure can be mechanically divided into a solid and liquid part. The solid portion (15–30% dry matter) can be composted, exported, or used as stall bedding. The liquids (4–8% dry matter) can be readily dispersed over crops using pump systems.

Biological control:
Organizations like the International Organization for Biological Control of Noxious Plants and Animals, the Commonwealth Institute of Biological Control, the United States Department of Agriculture/Agricultural Research Service (USDA/ARS), and the European Biological Control Laboratory support global search for possible biocontrol agents. Prior to introduction, quarantine and in-depth study of the organism's possible effectiveness and ecological effects are necessary to prevent agricultural pollution. Attempts are made to colonize and spread the biocontrol agent in suitable agricultural environments if authorized. Ongoing assessments of their effectiveness are carried out.

Anaerobic digestionIt involves employing microorganisms to biologically treat liquid animal feces in an air-free environment, which encourages the breakdown of organic materials. The garbage is heated with hot water to speed up the production of biogas. In addition to methane gas that may be burned directly on the biogas stove or in an engine generator to generate heat and electricity, the residual liquid is nutrient-rich and can be applied to fields as fertilizer. Approximately 20 times more potent than carbon dioxide, methane is a greenhouse gas that, if improperly managed, can have serious adverse impacts on the ecosystem. The most effective way to reduce the smell of manure management is to treat waste anaerobically.

Anaerobic digestion is also used in biological treatment lagoons to break down sediments, although it happens considerably more slowly. Unlike the heated digestion tanks, lagoons are maintained at room temperature. Lagoons do not function effectively in many northern U.S. climates because they need broad land expanses and substantial dilution flows. Reduced odor is another advantage of lagoons, and biogas is produced available for electricity and heating.

Studies have shown that aerobic digestion systems lower greenhouse gas emissions. In addition to facilitating producer adoption of environmentally better systems to replace existing anaerobic lagoons, GHG emission reductions and credits can assist offset the higher installation costs of cleaner aerobic technologies.

1. Characteristics of Wastewater
Agrochemical and pesticide wastewater has significant environmental issues because of its high levels of total dissolved solids (12000–13000 mg/L), biochemical and chemical oxygen demands (6000–7000 mg/L, 2000–3000 mg/L), and extremely alkaline pH (12–14). Wastewater from pesticides stands out due to its toxicity and environmental persistence.

2. Evolution of wastewater treatment Technologies
Before wastewater is applied to land, reused, or reintroduced into a body of water, it undergoes a multi-stage process called wastewater treatment. Reducing or eliminating organic debris, sediments, nutrients, pathogens, and other contaminants from wastewater is the aim.

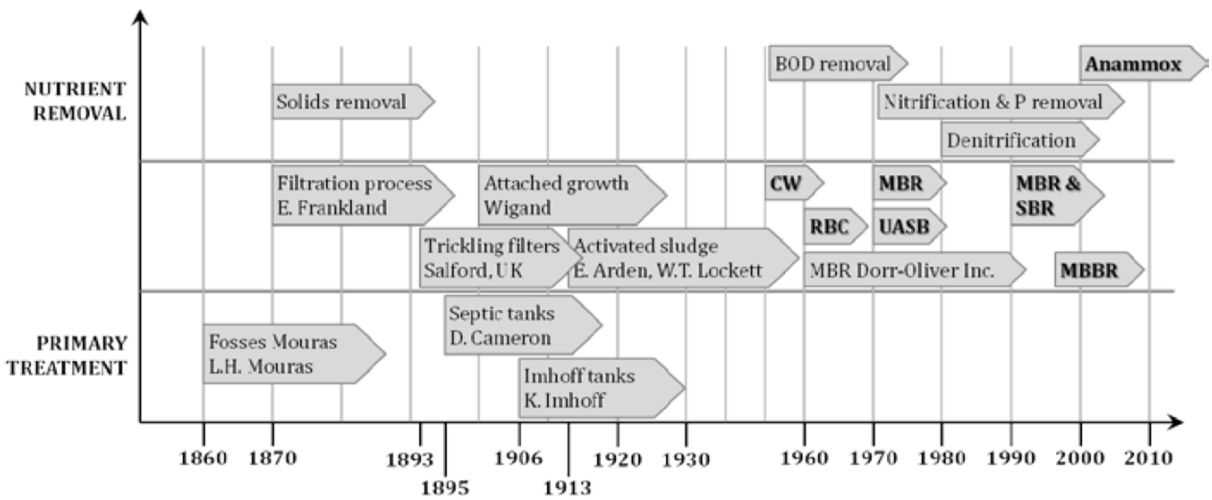

Fig. 3 : Evolution of wastewater treatment (Lofrano & Brown, 2010).

1. Conventional Treatment Technologies:

6.1 Preliminary Treatment:

Initial Care The wastewater is filtered for any particles and separated during the initial treatment. Grit chambers, bar screens, and comminutors are used to filter out debris such as sticks, toys, rags, leaves, sand, food particles, and gravel. The debris that has been separated is subsequently dumped in a landfill.

6.2 Primary Treatment:

Initial Care The wastewater is filtered for any particles and separated during the initial treatment. Grit chambers, bar screens, and comminutors are used to filter out debris such as sticks, toys, rags, leaves, sand, food particles, and gravel. The debris that has been separated is subsequently dumped in a landfill.

6.3 Secondary Treatment:

Aerobic methods are used to remove any leftover organic matter and suspended particles from the first treatment effluent. When aerobic microorganisms are present, organic matter breaks down into inorganic molecules like CO2, NH3, and others as part of aerobic biological treatments. Anaerobic and aerobic treatment technologies are the two categories into which secondary treatment technologies fall, and each is described in detail.

6.3.1 Aerobic Treatment Methods

Although aerobic biological wastewater treatment by itself is ineffective at removing nutrients from wastewater, it usually results in reductions of 20–30% in total phosphorus and total nitrogen (Nieuwstad et al., 1988). Adding a precipitation chemical to the activated sludge process—a procedure known as simultaneous precipitation—is the conventional way to enhance phosphorus removal.

Ferrous and ferric salts (such as ferrous sulfate and ferric chloride) and aluminum salts (such as aluminum sulphate) are the most frequently occurring precipitation chemicals. Rearranging the biological treatment stage (adding anaerobic and anoxic stages) to favor the growth of particular phosphorus-accumulating bacteria can improve biological phosphorus removal. The most common method for removing nitrogen from wastewaters is biological nitrification-denitrification.

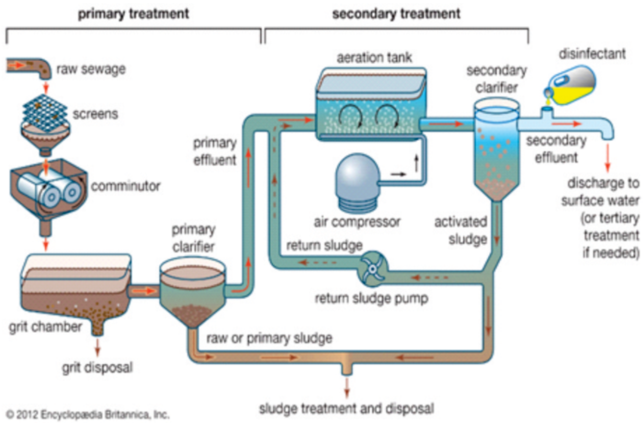

Fig. 4: Aerobic Treatment Methods (Activated Sludge Process).

6.1.1 Anaerobic Treatment Methods

UASB reactor treatment:

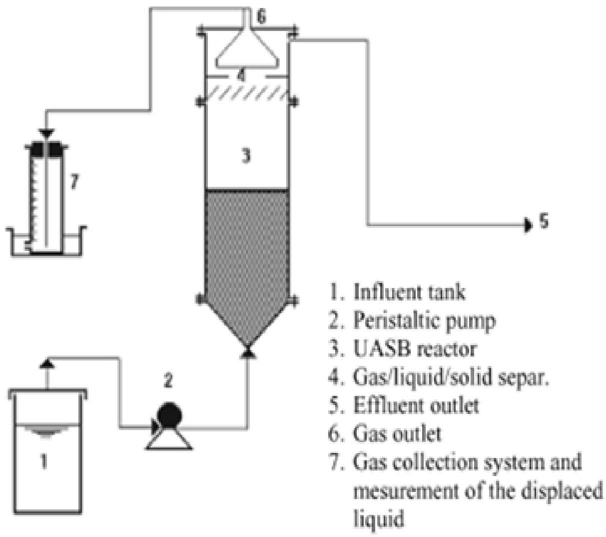

Fig. 5: Schematic diagram of UASB rector in Laboratory scale.

The basic advantages of a UASB reactor treatment unit are:

- It is economically practical,
- requires little land area for building, and uses little energy for operation.
- It is very easy to use, requires little experience, and produces a lot of sludge.
- When the reactor is operating properly, the odor output is controlled.

Anaerobic Attached Film Expanded Bed Reactor:

When there is no air present, wastewater is treated using this procedure. The following principle underlies its operation.

1. Hydrolysis, 2. Acidogenesis, 3. Acetogenesis
   4. Methanogenesis

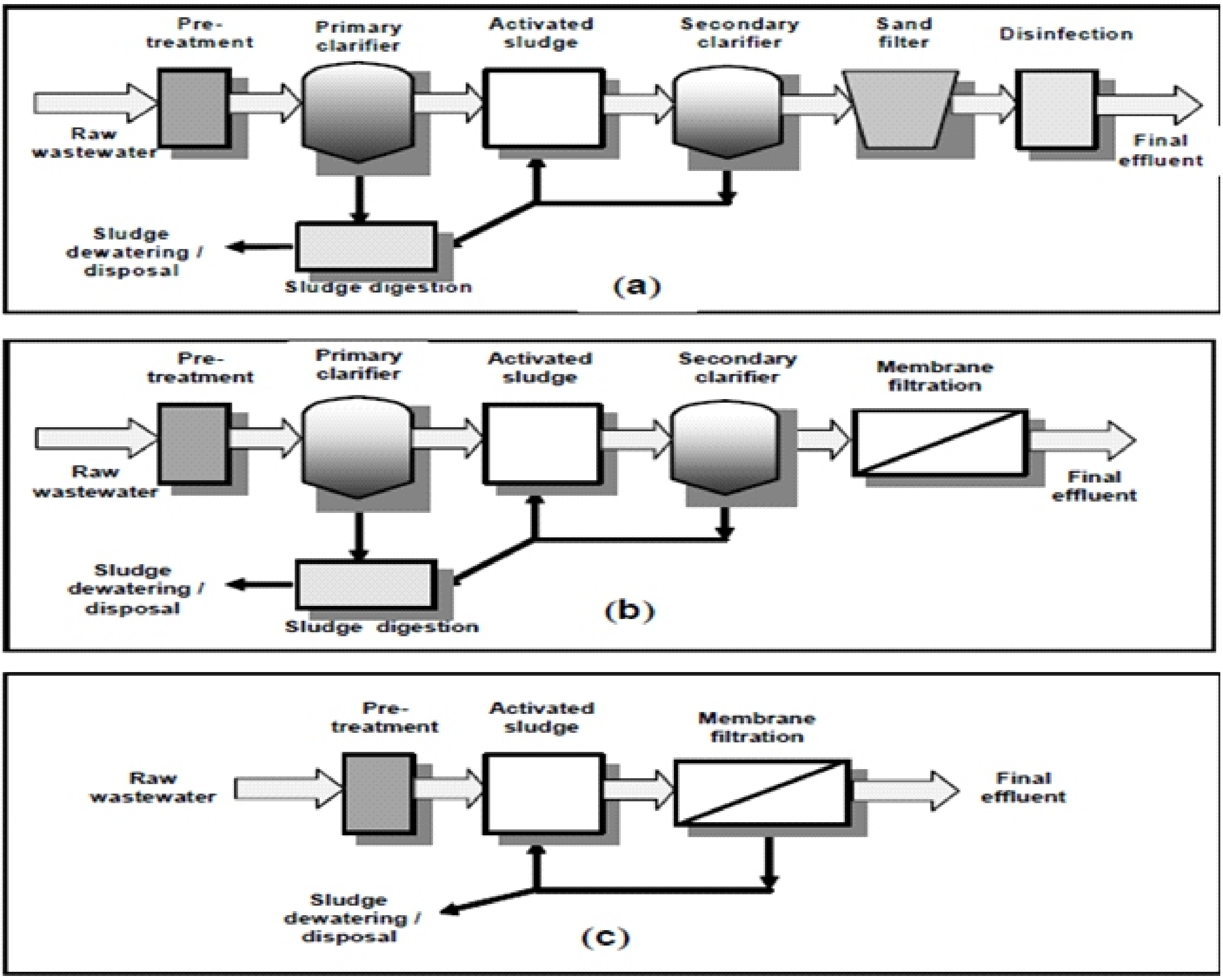

Fig 6: Flowcharts for (a) conventional wastewater treatment; (b) conventional treatment including tertiary membrane filtration; and (c) membrane bioreactors.

6.1.1 Advanced wastewater Treatment Technologies: Advanced therapeutic technologies include tertiary, physicochemical, and combined biological physical treatment. Following traditional wastewater treatment, tertiary (or advanced) treatment procedures can further enhance the wastewater effluent's quality. Organic particles, suspended particulates, synthetic organic compounds, enteric bacteria, and inorganic ions like phosphate and sulphate are usually eliminated from secondary effluents using tertiary treatment procedures.

For tertiary wastewater treatment, a variety of methods have been employed, such as post-precipitation, rapid sand filtration (RSF), slow sand filtration (SSF), dissolved air flotation (DAF), microfiltration, ultrafiltration, ion exchange, reverse osmosis, chemical oxidation, and carbon adsorption. The goal of treatment, wastewater quality and flow rate, the compatibility of various operations and processes, the ease of operating the process, the space requirements, and the system's economic and environmental viability are some of the factors that influence the applicability and choice of treatment process.

Biological, physicochemical, and hybrid technologies are a few of the more sophisticated wastewater treatment methods. Systems for biologically enhanced phosphorous removal (BEPR) and intermittently decanted extended aeration lagoons (IDEAL) for nitrogen removal are examples of biological treatment technology. These create the groundwork for further treatment procedures but do not create water that may be reused. Deep bed filtration and membrane filtration are examples of physiochemical processes.

Both of these techniques yield reused water and offer the benefits of simplicity and low sludge production, respectively. Membrane reactors, which combine physiochemical and biological processes, are classified as hybrid treatment methods since they offer the aforementioned advantages all at once.

Physicochemical Process of Treatment: Physicochemical treatment appears to be a feasible alternative for treating agricultural wastewater. Alum, poly aluminum chloride (PAC), ferrous sulphate (FeSO4), and polyelectrolyte are a few common coagulates that were chosen for treatment based on the research review. Alum, poly aluminum chloride (PAC), and ferrous sulphate (FeSO4) can be used separately or in conjunction with polyelectrolyte.

Membrane Bioreactor Technology (MBR): Physicochemical treatment appears to be a feasible alternative for treating agricultural wastewater. Alum, poly aluminum chloride (PAC), ferrous sulphate (FeSO4), and polyelectrolyte are a few common coagulates that were chosen for treatment based on the research review. Alum, poly aluminum chloride (PAC), and ferrous sulphate (FeSO4) can be used separately or in conjunction with polyelectrolyte.

Rather, low-pressure membrane filters like reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) or microfiltration (MF) are used to separate the effluent from the activated sludge. Both sidestream and submerged configuration models of MBR are available; however, the submerged design is utilized for treating municipal wastewater. Membrane reactors could be used to eliminate ibuprofen, diclofenac, estrone (E1), and 17α-ethinylestradiol (EE2) (Kruglova et al. 2016).

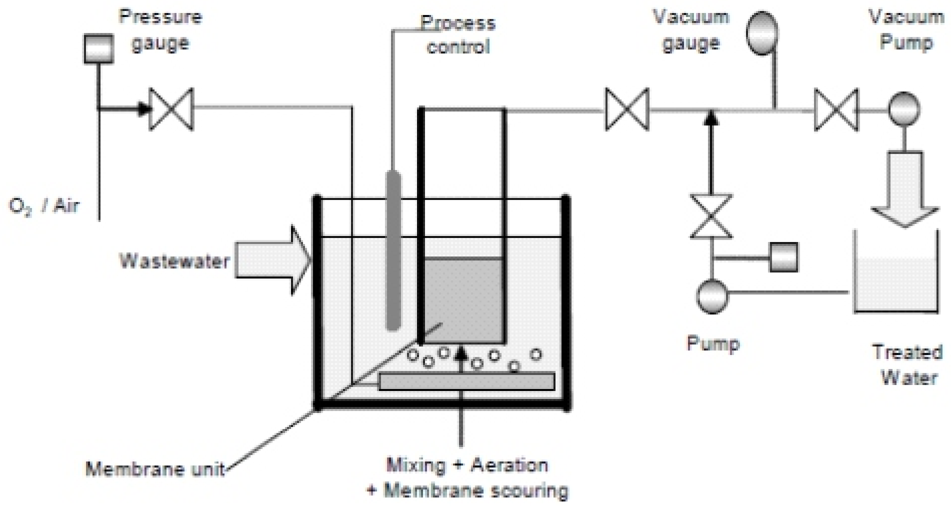

Fig 7: Schematic of integrated (submerged) MBR.

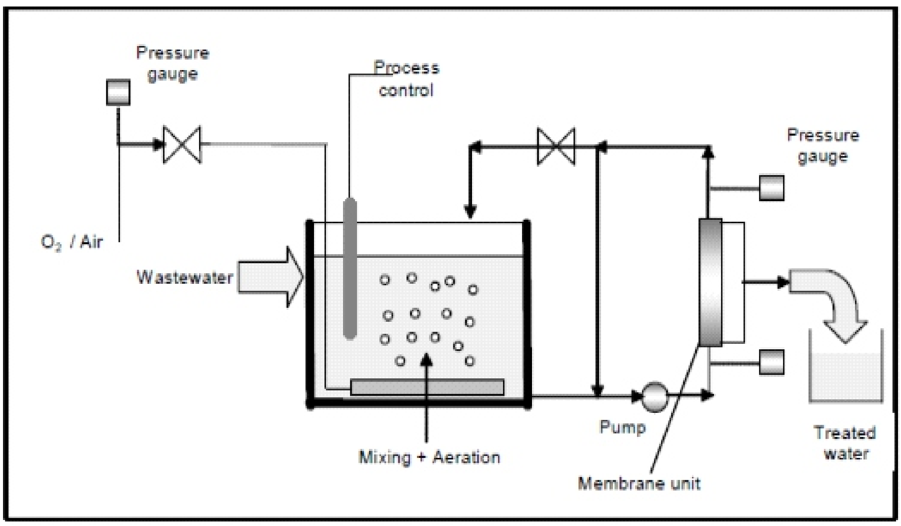

Fig 8 : Schematic of recirculated (external) MBR.

Wastewater disinfection: By putting the water through a different disinfection procedure after secondary or tertiary wastewater treatment, enteric bacteria can be further eliminated from the wastewater effluents. Chemical and physical treatments are the two categories of water disinfection techniques. Chlorine gas (Cl2), hypochlorite (sodium hypochlorite, NaOCl; calcium hypochlorite, Ca(OCl)2), chloramines, chlorine dioxide (ClO2), ozone (O3), and peracetic acid (PAA) are examples of chemical disinfectants. The most crucial physical disinfection technique for water and wastewater is ultraviolet (UV) irradiation, which can dramatically reduce the number of enteric microorganisms in primary, secondary, or tertiary wastewater effluents, hence lowering microbial burdens in receiving natural waterways.

Peracetic acid was shown to be an effective disinfectant against intestinal bacteria in laboratory-scale disinfection tests using a synthetic test media. A 10-minute contact duration and 1.5–3 mg/l of PAA produced roughly 2-3 log (99–99.9%) E. Coli,

Enterococcus faecalis, and Salmonella enteritidis reductions: PAA demonstrated high disinfection efficacy against enterococci and total coliforms in pilot-scale disinfection of municipal secondary and tertiary effluents. The quantities of these indicator bacteria were generally decreased below 500 CFU/100 ml TC and 100 CFU/100 ml EC, and in many cases, to <10-100 CFU/100 ml. PAA doses of 2–7 mg/l and 27 min contact time produced around 3 log reductions of these bacteria.

Previous studies have reported approximately similar PAA disinfection efficiencies against enteric bacteria (Collivignarelli et al., 2000; Stampi et al., 2001; Wagner et al., 2002; Caretti and Lubello, 2003). However, the inactivation of enteric bacteria has been achieved in some studies using slightly higher PAA doses (around 10 mg/l) (Lazarova et al., 1998; Liberti and Notarnicola, 1999). The variations in reactor design, water quality, and operating conditions among the various trials may account for the necessity for larger PAA dosages.

The results also suggest that a combined PAA/UV disinfection treatment may achieve synergistic benefits and improved disinfection efficiency.

1. Nanotechnology in Wastewater Treatment:

One of the best and most cutting-edge methods for treating wastewater is nanotechnology. The success of nanotechnology can be attributed to a number of factors, including the extremely high interacting, absorbing, and reacting capacities of nanoparticles, which result from their small size and enormous surface area. They can even be combined to create colloidal solutions with aqueous suspensions. Because of their small size, nanoparticles are able to conserve energy. Given the strong technological demand for nanoparticle-based water treatment, its cost should be controlled in accordance with market competitiveness (Crane and Scott 2012).

Recent developments in a variety of nanomaterials, including molecularly imprinted polymers (MIPs), bioactive nanoparticles, nanosorbents, biomimetic membranes, nanostructured catalytic membranes, and nanocatalysts, have been applied to the elimination of harmful metal ions, disease-causing microorganisms, and inorganic and organic solutes from water.

7.1 Nanocatalysts

Because of their large surface area, nanocatalysts exhibit great catalytic activity. Because they accelerate the rate of degradation and improve the reactivity of pollutants, nanocatalysts are employed to treat wastewater. Nanocatalysts such as semiconductor materials, zero-valence metals, and bimetallic nanoparticles can degrade environmental contaminants like azo dyes, halogenated aliphatics, polychlorinated biphenyls (PCBs), organ chlorine pesticides, halogenated herbicides, and nitro aromatics (Xin et al. 2011).

Silver (Ag) nanocatalysts, N-doped TiO2 catalysts, and ZrO2 nanoparticles are all highly effective at breaking down microbiological pollutants. The reusability of these nanocatalysts is an added benefit (Shalini et al. 2012). The removal of Cr (IV) from wastewater is accomplished using TiO2-AGs.

The altered TiO2 nanoparticles cause a change in their absorption band from the ultraviolet to the visible spectrum. As a result, TiO2-AGs are highly effective at eliminating Cr (IV) from wastewater. Halogenated organic compounds (HOCs) and other pollutants are difficult to break down and call for sophisticated nanocatalytic processes.

.

Consequently, the HOCs undergo biodegradation in the treatment plant after first being treated with Pd nanocatalysts. The reaction's reducing agent might be either hydrogen or formic acid, depending on the degree of contamination. The utilized nanocatalyst is easily removed from the reaction mixture and then reused because of its ferromagnetism (Hildebrand et al. 2008).

Palladium-incorporated ZnO nanoparticles (Khalil et al. 2011) and WO3 nanocatalysts (Khalil et al. 2009) could be used to eliminate E. coli cells. Marcells et al. (2009) used palladium nanoparticles (PdNPs) to investigate the reduction of Cr (IV) to Cr (II). The combination of nanocatalysts with nanosorbents could result in the combined sorption and degradation of the pollutants. By employing tetrahydrofuran treatment to activate the silver and amidoxime fiber nanocatalysts, organic dye remediation can be accomplished (Zhi et al. 2010). ZnO nanoparticles doped with Sm (samarium) could effectively remove the monoazo dye Acid Blue 92 (AB92) (Khataee et al. 2016).

7.2 Nanosorbents

The United States and Asia are the primary markets for the use of nanosorbents in water treatment procedures. Their sorption capability for various pollutants is high and selective. One benefit of the nanosorbents is their ability to be eliminated from the treatment area, which lowers toxicity. Regenerated nanosorbents are also more affordable and widely used in industry.

Nanosorbents are removed from the treatment sites using a variety of techniques, including ion exchangers, magnetic forces, cleaning chemicals, and many more. To create magnetic nanoparticles, particular ligands with particular affinities are placed on top of the particles (Apblett et al. 2001). Nanosorbents, such as poly (aniline-co-5-sulfo-2-anisidine), can be used to extract silver ions as silver nanocrystals (Li et al. 2010).

Nanoclays are used to remove phosphorus and hydrocarbon stains. Magnetic nanosorbents can be used to remove organic pollutants from wastewater (Campos et al. 2012). Excellent mechanical strength, chemical resistance, high specific surface area, and outstanding adsorption capacity are all attributes of carbon-based nanosorbents. According to Lee et al. (2012), they are employed to treat water that contains nickel. Mesoporous silica, chitosan, and dendrimers are employed as nanosorbents to remove heavy metal ions from contaminated water because of their distinct chemical and physical characteristics (Vunain et al. 2016).

7.3 Bioactive Nanoparticles

Chlorine-free biocides known as bioactive nanoparticles are becoming a new tool for wastewater treatment. Gram-positive and gram-negative bacteria as well as bacterial spores can be effectively killed by magnesium oxide nanoparticles and cellulose acetate (CA) fibers that have embedded silver nanoparticles (Nora and Mamadou 2005). Due to their nontoxicity, biological compatibility, and ease of modification with functional groups, mesoporous silica nanoparticles may also find application in wastewater treatment procedures (Gunduz et al. 2015). Both microbial and pathogen detection as well as diagnostics will benefit from current and developing nanotechnology techniques for microbial pathogen detection.

7.4 Molecularly Imprinted Polymers (MIPs)

The process of free radical polymerization to a crosslinker is known as molecular imprinting. One of the best new methods for biological, environmental, and pharmacological applications is molecularly imprinted polymers, or MIPs. According to Hande et al. (2015) and Mattiasson (2015), they are inexpensive, straightforward, durable, selective, and nonbiodegradable. The semi-covalent, covalent, and non-covalent binding of the functional groups of appropriate monomers to the template gives MIPs access to the particular binding sites.

The MIPs are excellent absorbents and have a highly selective nature as a result of this alteration. According to Caro et al. (2006), it is utilized for wastewater treatment and the identification of contaminants, even at extremely low concentrations. The MIPs' ability to be selective gives them a significant edge over other methods. Nano-MIPs are created using the mini-emulsion polymerization process to adsorb micropollutants from hospital effluent.

The nano-MIPs have a particle size range of 50–500 nm. After treatment, nano-MIPs might be coated with magnetic core to be removed from the wastewater (Tino et al. 2009). MIPs encapsulated in nanofibers utilizing the electro-spinning technique are utilized to treat the pollution produced during wastewater treatment. MIPs were used to create a sensor that measures the amount of phosphate in wastewater. Unlike traditional techniques like colorimetry, the proposed sensor was easily portable, had a detection limit of 0.16 mg P/L, and did not require sample filtration for monitoring (Warwick et al. 2014). Cd (II), Pb (II), As (V), Hg (II), Ag, Au, Pt, Pd, acitindes, and lanthanides could all be eliminated using MIPs (Hande et al. 2015).

7.5 Nanostructured Catalytic Membranes (NCMs)

The advantages of nanostructured catalytic membranes (NCMs) are their capacity for optimization, short catalyst contact time, homogeneous catalytic sites, ease of industrial scale-up, and the ability to support sequential reactions.

According to Hyeok et al. (2009), membranes exposed to UV radiation and nanostructured TiO2 films aid in the degradation of organic pollutants, physical separation of water contaminants, anti-biofouling activity, and inactivation of microorganisms. Numerous membranes, including chitosan, polyvinylidene fluoride (PVDF), cellulose acetate, polysulfone, and many more, could immobilize the metallic nanoparticles. According to Jian et al. (2009), the immobilized metallic nanoparticles have several benefits, including low agglomeration, high reactivity, decreased surface passivation, and organic portioning.

Palladium acetate and polyetherimide have been used to create nanocomposite films, and the effectiveness of the water treatment process has been demonstrated by research into the particular interactions between hydrogen and the Pd-based nanoparticles. By annealing the precursor film under various circumstances utilizing both the in situ and ex situ methods, the metal nanoparticles were produced within the matrix.

This gives designers the chance to create materials with adjustable qualities (Clemenson et al. 2010). According to Hongwei et al. (2012), the N-doped "nutlike" ZnO nanostructured materials demonstrated antibacterial action, generated clean water with a steady high flux, and effectively eliminated water pollutants by boosting photodegradation activity.

8. Conclusions

Protecting the environment and public health requires efficient wastewater treatment, especially in agricultural areas where water contamination is becoming a bigger problem. Although traditional techniques such as filtration, sedimentation, and biological treatments provide fundamental answers, they frequently fail to satisfy contemporary reuse requirements. Innovative approaches to getting rid of complex pollutants including dyes, heavy metals, and organic contaminants are provided by advanced technologies like membrane bioreactors, nanosorbents, nanocatalysts, molecularly imprinted polymers, and bioactive nanoparticles. Wastewater management is made more effective, economical, and sustainable by combining classic and cutting-edge methods. Issues including system upkeep, financial viability, and public awareness need to be resolved if the advantages of these approaches are to be fully realized. Making wastewater a useful resource for sustainable agriculture and human well-being requires a multidisciplinary approach backed by technology, policy, and community involvement.

REFERENCES

1. **Ahmed, M., Rao, S., & Patel, V.** (2023). Precision agriculture for sustainable nutrient management: A global perspective. *Environmental Monitoring and Assessment*. 195(2), 145. https://doi.org/10.1007/s10661-023-10893-z
2. **Alagha, O.; Allazem, A.; Bukhari, A.A.; Anil, I.; Mu'azu, N.D.** Suitability of SBR for wastewater treatment and reuse: Pilot-Scale reactor operated in different anoxic conditions. *Int. J. Environ. Res. Public Health*. 2020, 17, 1617. [CrossRef] [PubMed]
3. **Al-Juaidi, A.E.; Kaluarachchi, J.J.; Mousa, A.I.** Hydrologic-economic model for sustainable water resources management in a coastal aquifer. *J. Hydrol. Eng.* 2014, 19, 04014020. [CrossRef].
4. **Apblett AW, Al-Fadul SM, Chehbouni M, Trad T** (2001) Proceedings of the 8th international environmental petroleum consortium.
5. **Awad, H.; Alalm, M.G.; El-Etriby, H.K.** Environmental and cost life cycle assessment of different alternatives for improvement of wastewater treatment plants in developing countries. *Sci. Total Environ*. 2019, 660, 57–68. [CrossRef] Sustainability 2023, 15, 10940 28 of 31.
6. **Baskar, A.V.; Bolan, N.; Hoang, S.A.; Sooriyakumar, P.; Kumar, M.; Singh, L.; Jasemizad, T.; Padhye, L.P.; Singh, G.; Vinu, A.;** et al. Recovery, regeneration and sustainable management of spent adsorbents from wastewater treatment streams: A review. *Sci. Total Environ*. 2022, 822, 153555. [CrossRef]
7. **Canaj, K.; Mehmeti, A.; Morrone, D.; Toma, P.; Todorovi´c, M**. Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: A case study in southern Italy. *J. Clean. Prod.* 2021, 293, 126142. [CrossRef]
8. **Capodaglio, A.G.** Fit-for-purpose urban wastewater reuse: Analysis of issues and available technologies for sustainable multiple barrier approaches. *Crit. Rev. Environ. Sci. Technol*. 2021, 51, 1619–1666. [CrossRef]
9. **Caro E, Marce´ RM, Borrull F, Cormack PAG, Sherrington DC** (2006) Application of molecularly imprinted polymers to solid-phase extraction of compounds from environmental and biological samples. *Trends Anal Chem* 25(2):143–154.
10. **Chen, L., Yu, M., & Han, X.** (2024). Antibiotics and hormones in agricultural water sources: A case study in Eastern China. *Water Research*. 245,

120089. https://doi.org/10.1016/j.watres.2024.120089

11. **Chojnacka, K.; Witek-Krowiak, A.; Moustakas, K.; Skrzypczak, D.; Mikula, K.; Loizidou, M.** A transition from conventional irrigation to fertigation with reclaimed wastewater: Prospects and challenges. *Renew. Sustain. Energy Rev.* 2020, 130, 109959. [CrossRef]
12. **Chu, J.; Chen, J.; Wang, C.; Fu, P.** Wastewater reuse potential analysis: Implications for China's water resources management. *Water Res.* 2004, 38, 2746–2756. [CrossRef]
13. **Cle´menson S, Espuche E, David L, Le´onard L** (2010) Nanocomposite membranes of polyetherimide nanostructured with palladium particles: processing route, morphology and functional properties. *J Membr Sci* 361(1–2): 167–175.
14. **Crane RA, Scott TB** (2012) Nanoscale zero-valent iron: future prospects for an emerging water treatment technology. *J Hazard Mater* 211–212:112–125.
15. **Dutta, D.; Arya, S.; Kumar, S.** Industrial wastewater treatment: Current trends, bottlenecks, and best practices. *Chemosphere* 2021, 285, 131–245. [CrossRef]
16. **Fagundes, M., Fagundes, T. R. S., Fagundes, F. D. S., & Ribeiro, G. S.** (2024). Leptospirosis outbreak in southern Brazil following historic flooding: An urgent call for climate and public health action. *Infectious Disease Reports*, 4(3), 28. https://doi.org/10.3390/idr4030028.
17. **FAO** 2013, Guidelines to control water pollution from agriculture in China, Water Report 40.
18. **FAO**. 2006. Livestock's long shadow. Rome, Food and Agriculture Organization of the United Nations (FAO).
19. **FAO**. 2013. Tool kit: reducing the food wastage footprint. Rome, Food and Agriculture Organization of the United Nations (FAO).
20. **FAO**. 2014. Area equipped for irrigation. Infographic. AQUASTAT: FAO's information system on water and agriculture. Rome, Food and Agriculture Organization of the United NationFAO)(availableat:http://www.fao.org/nr/water/aquastat/infographics/Irrigation_eng.pdf).
21. **FAO**. 2015. Global initiative of food loss and waste. Rome, Food and Agriculture.
22. **FAO**. 2016a. FAOSTAT. Database. Available at http://faostat3.fao.org/browse/R/ RP/E Accessed July 2016. Rome, Food and Agriculture Organization of the United Nations (FAO).
23. **FAO**. 2016b. The State of World Fisheries and Aquaculture: Contributing to food security and nutrition for all. Rome, Food and Agriculture Organization of the United Nations (FAO).
24. **Fernández, C., Rodríguez, J., & López, D.** (2020). Role of vegetated buffer strips in reducing agricultural runoff. *Agricultural Water Management*, 238, 106222. https://doi.org/10.1016/j.agwat.2020.106222
25. **Fito, J.; Van Hulle, S.W.** Wastewater reclamation and reuse potentials in agriculture: Towards environmental sustainability. *Environ. Dev. Sustain.* 2021, 23, 2949–2972. [CrossRef]
26. **Gikas, P.; Tchobanoglous, G.** The role of satellite and decentralized strategies in water resources management. *J. Environ. Manag.* 2009, 90, 144–152. [CrossRef]
27. **Gao, X., Liu, J., & Wang, T.** (2022). Nutrient pollution and eutrophication: Emerging issues in freshwater ecosystems. *Journal of Environmental Sciences*, 113, 52–64. https://doi.org/10.1016/j.jes.2022.01.009
28. **Geo24 News.** (2024, November 24). India's ban on antibiotics in animal food products to help curb AMR: Report. https://www.geo24news.com/science-tech/2024/11/24/indias-ban-on-antibiotics-in-animal-food-products-to-help-curb-amr-report
29. **Gunduz O, Yetmez M, Sonmez M, Georgescu M, Alexandrescu L, Ficai A, Ficai D, Andronescu E** (2015) Mesoporous materials used in medicine and environmental applications. *Curr Top Med Chem.* 15(15):1501–1515.
30. **Hande PE, Samui AB, Kulkarni PS** (2015) Highly selective monitoring of metals by using ion-imprinted polymers. *Environ Sci Pollut Res Int* 22(10):7375–7404. doi:10.1007/s11356- 014-3937-x . Epub 2015 Feb 7.
31. **Hildebrand H, Mackenzie K, Kopinke FD** (2008) Novel nano-catalysts for wastewater treatment. *Glob Nest J* . 10(1):47–53.
32. **Hongwei B, Zhaoyang L, Darren DS** (2012) Hierarchical ZnO nanostructured membrane for multifunctional environmental applications. *Colloids Surf A Physicochem Eng Asp* 410 (20):11–17.
33. https://en.wikipedia.org/wiki/Agricultural_waste water_treatment

34. **Issaoui, M.; Jellali, S.; Zorpas, A.A.; Dutournie, P.** Membrane technology for sustainable water resources management: Challenges and future projections. *Sustain. Chem. Pharm.* 2022, 25, 100590. [CrossRef]

35. **Jamrah, A.; Al-Futaisi, A.; Prathapar, S.; Harrasi, A.A.** Evaluating greywater reuse potential for sustainable water resources management in Oman. *Environ. Monit. Assess.* 2008, 137, 315–327. [CrossRef]

36. **Jhansi, S.C.; Mishra, S.K.** Wastewater treatment and reuse: Sustainability options. Consilience 2013, 10, 1–15.

37. **Jian X, Leonidas B, Dibakar B**. (2009) Synthesis of nanostructured bimetallic particles in poly ligand functionalized membranes for remediation applications. In: Nanotechnology applications for clean water. William Andrew Publishing, Norwich, pp 311–335.

38. **Kamali, M.; Persson, K.M.; Costa, M.E.; Capela, I.** Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: Current status and future outlook. *Environ. Int.* 2019, 125, 261–276. [CrossRef]

39. **Kamble, S.; Singh, A.; Kazmi, A.; Starkl, M.** Environmental and economic performance evaluation of municipal wastewater treatment plants in India: A life cycle approach. *Water Sci. Technol.* 2019, 79, 1102–1112. [CrossRef]

40. **Kesari, K.K.; Soni, R.; Jamal, Q.M.; Tripathi, P.; Lal, J.A.; Jha, N.K.; Siddiqui, M.H.; Kumar, P.; Tripathi, V.; Ruokolainen, J.** Wastewater treatment and reuse: A review of its applications and health implications. *Water Air Soil Pollut.* 2021, 232, 208. [CrossRef]

41. **Khalil A, Gondal MA, Dastageer MA** (2009) Synthesis of nano-WO3 and its catalytic activity for enhanced antimicrobial process for water purification using laser induced photo-catalysis. *Catal Commun* 11(3):214–219.

42. **Khalil A, Gondal MA, Dastageer MA** (2011) Augmented photocatalytic activity of palladium incorporated ZnO nanoparticles in the disinfection of Escherichia coli microorganism from water. *Appl Catal A Gen* 402(1–2):162–167.

43. **Khan, S.A.; Ponce, P.; Yu, Z.; Golpîra, H.;** Mathew, M. Environmental technology and wastewater treatment: Strategies to achieve environmental sustainability. *Chemosphere* 2022, 286, 131532. [CrossRef]

44. **Khataee A, Saadi S, Vahid B, Joo SW, Min BK** (2016) Sonocatalytic degradation of Acid Blue 92 using sonochemically prepared samarium doped zinc oxide nanostructures. *Ultrason Sonochem* 29:27–38. doi:10.1016/j.ultsonch.2015.07.026. Epub 2015 Aug 28.

45. **Kim, J.H.; Behera, S.K.; Oh, S.Y.; Park, H.S.** Reuse potential of municipal wastewater treatment facility effluents for sustainable water resource management in Ulsan, Korea. *Water Environ. J.* 2010, 24, 293–302. [CrossRef]

46. **Kruglova A, Kra°kstr€om M, Riska M, Mikola A, Rantanen P, Vahala R, Kronberg L** (2016) Comparative study of emerging micropollutants removal by aerobic activated sludge of large laboratory-scale membrane bioreactors and sequencing batch reactors under low-temperature conditions. *Bioresour Technol* 214:81–88. doi:10.1016/j.biortech.2016.04.037. [Epub ahead of print].

47. **Kumar, A., Sharma, R., & Tiwari, S.** (2023). Agricultural runoff and water pollution in South Asia: A systematic review. *Environmental Pollution*, 314, 120359. https://doi.org/10.1016/j.envpol.2022.120359

48. **Lee XJ, Foo LPY, Tan KW, Hassell DG, Lee LY** (2012) Evaluation of carbon-based nanosorbents synthesised by ethylene decomposition on stainless steel substrates as potential sequestrating materials for nickel ions in aqueous solution. *J Environ Sci.* 24(9):1559–1568.

49. **Li XG, Feng H, Huang MR** (2010) Redox sorption and recovery of silver ions as silver nanocrystals on poly (aniline-co-5-sulfo-2-anisidine)nanosorbents. Chemistry 16 (33):10,113–10,123. doi:10.1002/chem.201000506.

50. **Li, Y., Zhao, Q., & Zhang, M.** (2021). Emerging contaminants in water sources from livestock farming regions. Science of The Total Environment, 765, 144189. https://doi.org/10.1016/j.scitotenv.2020.144189

51. **Liao, Z.; Chen, Z.; Xu, A.O.; Gao, Q.; Song, K.; Liu, J.; Hu, H.Y.** Wastewater treatment and reuse situations and influential factors in major Asian countries. *J. Environ. Manag.* 2021, 282, 111976. [CrossRef] [PubMed]

52. **Libhaber, M.; Orozco-Jaramillo, Á.** Sustainable Treatment and Reuse of Municipal Wastewater: For Decision Makers and Practising Engineers; Iwa Publishing: London, UK, 201.

53. **Marcells A, Omole IK, Omowunmi O, Sadik A** (2009) Nanostructured materials for improving water quality: potentials and risks. In: Nanotechnology applications for clean water. William Andrew Publishing, Norwich, pp 233–247.

54. **Mattiasson B**. (2015) MIPs as tools in environmental biotechnology. *Adv Biochem Eng Biotechnol* 150:183–205. doi:10.1007/10_2015_311.

55. Organization of the United Nations (FAO).

56. **Shalini CA, Pragnesh N, Dave A, Shah NK** (2012) Applications of nano-catalyst in new era. *J Saudi Chem Soc* .16(3):307–325

57. **Singh, V., Meena, H., & Chauhan, A.** (2020). Livestock waste management and water pollution: Challenges and solutions. Ecological Indicators, 112, 106082. https://doi.org/10.1016/j.ecolind.2020.106082

58. **The Guardian.** (2024, September 27). 'Rivers you think are pristine are not': How drug pollution flooded the UK's waterways – and put human health at risk. https://www.theguardian.com/environment/2024/sep/27/amr-drug-resistance-england-national-parks-hidden-hazards-rivers-pollution-aoe

59. **Tino S, Achim W, Klaus N, Jürgen R, Dieter B, Thomas H, Guenter EMT** (2009) Water treatment by molecularly imprinted polymer nanoparticles. MRS Spring Meeting. Camb J Online 11:69

60. **Ventresque C, Turner G, Bablon G** (1997) Nanofiltration: from prototype to full scale. *J Am Water Works Assoc* 89(10):65–76.

61. **Tortajada, C.** Contributions of recycled wastewater to clean water and sanitation Sustainable Development Goals. NPJ Clean Water 2020, 3, 22. [CrossRef].

60. **UNEP.** (2021). Global assessment of water pollution from agriculture: Trends and solutions. United Nations Environment Programme.

62. **UNEP.** 2016. A snapshot of the world's water quality: towards a global assessment. Nairobi, United Nations Environment Programme (UNEP).

63. **US EPA** 2016. Water quality assessment and TMDL information. Washington, DC,United States Environmental Protection Agency (US EPA) (available at: https://ofmpub.epa.gov/waters10/attains_index.home).

64. **Villarín, M.C.; Merel, S.** Paradigm shifts and current challenges in wastewater management. *J. Hazard. Mater.* 2020, 390, 122–139. [CrossRef] [PubMed].

65. **Vunain E, Mishra AK, Mamba BB** (2016) Dendrimers, mesoporous silicas and chitosan-based nanosorbents for the removal of heavy-metal ions: a review. *Int J Biol Macromol* 86:570–586. doi:10.1016/j.ijbiomac.2016.02.005 . Epub 2016 Feb 3

66. **Wang, Y., Liu, X., & Chen, Z.** (2022). Climate variability and nutrient runoff in agricultural watersheds. Hydrology and Earth System Sciences, 26(3), 809–824. https://doi.org/10.5194/hess-26-809-2022

67. **WHO**. 2012. Animal waste, water quality and human health. Geneva, Switzerland, World Health Organization.

68. **WWAP** 2015. The United Nations World Water Development Report 2015: Water for a sustainable world. United Nations World Water Assessment Programme (WWAP). Paris, United Nations Educational, Scientific and Cultural Organization.

69. **WWAP.** 2013. The United Nations World Water Development Report 2013. United Nations World Water Assessment Programme (WWAP). Paris, United Nations Educational, Scientific and Cultural Organization.

70. **WWAP.** 2017. The United Nations World Water Development Report 2017: Wastewater, the untapped resource. United Nations World Water Assessment Programme (WWAP). Paris, United Nations Educational, Scientific and Cultural Organization.

71. **Xin Z, Lu L, Bingcai P, Weiming Z, Shujuan Z, Quanxing Z** (2011) Polymer-supported nanocomposites for environmental application: a review. *Chem Eng J* 170(2–3):381–394.

72. **Yoo RS, Brown DR, Pardini RJ, Bentson GD** (1995) Microfiltration: a case study. *J Am Water Works Assoc.* 87(3):38–49.

73. **Zhang, L., Huang, J., & Wu, Y.** (2021). Agricultural intensification and water quality degradation: A review of global trends and local impacts. *Journal of Cleaner Production*, 280, 124345. https://doi.org/10.1016/j.jclepro.2020.124345.

74. **Zhi CW, Yong Z, Ting XT, Lifeng Z, Hao F** (2010) Silver nanoparticles on amidoxime fibers for photo-catalytic degradation of organic dyes in waste water. *Appl Surf Sci.* 257(3):1092–1097.