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Evaluation of the purification performance of a trickling filter

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Dedication

To my dear parents, For your endless love, unwavering support, and countless sacrifices. You are my greatest source of inspiration and strength. This achievement is yours as much as it is mine.

To myself, For never giving up, for enduring every challenge, and for believing that I could. This work stands as a symbol of my resilience and determination.

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✍HADJI AYA

Abstract

The dairy industry produces large volumes of wastewater containing high concentrations of organic matter, such as lactose, proteins, and fats, which pose serious environmental risks if discharged untreated. This study aimed to evaluate the treatment performance of a fixed-film biological reactor for synthetic dairy effluent under laboratory conditions. The focus was on monitoring the removal of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand over five days (BOD_5), and pH evolution during treatment.

Different influent flow rates, ranging from 0.63 to 0.76 L/min, were tested to assess their impact on biofilm activity and removal efficiency. The reactor showed high performance, with COD removal reaching 88–90% at 0.63 L/min and BOD_5 removal peaking at 100% at 0.73 L/min. Despite slight fluctuations, the biofilm maintained a stable activity, and the pH remained in the optimal range for microbial growth (8.0–8.4).

The results confirm the feasibility of using fixed-film reactors for dairy wastewater treatment. These systems offer advantages such as compact design, operational stability, and high organic load resistance. This work supports the development of efficient and eco-friendly technologies for agro-industrial effluent management.

Keywords: Dairy effluent, Fixed-film reactor, COD, BOD_5, Biofilm, Wastewater treatment.

الملخص

تنتج صناعة الألبان كميات كبيرة من المياه العادمة المحملة بتركيزات عالية من المواد العضوية مثل اللاكتوز والبروتينات والدهون، مما يشكل خطرًا بيئيًا كبيرًا إذا لم تتم معالجتها. تهدف هذه الدراسة إلى تقييم كفاءة مفاعل بيولوجي ذي وسط ثابت لمعالجة نفايات لبنية صناعية تحت ظروف مخبرية. ركزت الدراسة على إزالة الطلب الكيميائي للأكسجين (COD) والطلب البيوكيميائي للأكسجين خلال خمسة أيام(BOD_5) ، إضافة إلى مراقبة تطور الرقم الهيدروجيني.

تم اختبار معدلات تدفق مختلفة (من 0.63 إلى 0.76 لتر/دقيقة) لدراسة تأثيرها على فعالية البيوفيلم وكفاءة المعالجة. أظهر النظام أداءً عالياً، حيث وصلت إزالة COD إلى 88–90% عند 0.63 لتر/دقيقة، وبلغت إزالة BOD_5 حدها الأقصى بنسبة 100% عند 0.73 لتر/دقيقة. وعلى الرغم من بعض الاضطرابات، حافظ البيوفيلم على نشاط مستقر، كما بقي الرقم الهيدروجيني ضمن المجال المثالي لنمو البكتيريا (8.0–8.4).

تؤكد النتائج فعالية استخدام المفاعلات ذات الوسط الثابت في معالجة مياه الصرف الخاصة بصناعة الألبان، لما تتميز به من تصميم مدمج واستقرار تشغيلي وقدرة عالية على مقاومة الأحمال العضوية. تدعم هذه الدراسة تطوير تقنيات فعالة وصديقة للبيئة لمعالجة مياه الصرف الزراعية والصناعية.

الكلمات المفتاحية :نفايات الألبان، مفاعل ذو وسط ثابت، COD، BOD_5، البيوفيلم، معالجة المياه المستعملة.

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General introduction

The development of the agri-food industry, while essential to both the economy and food security, is increasingly associated with the generation of highly polluted wastewater. Among these industries, the dairy sector stands out due to the substantial volume of wastewater it produces—estimated at 3 to 6 liters per liter of milk processed. These effluents are characterized by high levels of biodegradable organic matter, fats, lactose, proteins, and mineral salts, making their treatment a crucial environmental priority before any discharge into natural ecosystems.

The nature and composition of dairy wastewater vary depending on the specific dairy products manufactured (such as pasteurized milk, yogurt, cheese, etc.) and the industrial processes involved. These effluents, typically rich in Chemical Oxygen Demand (COD), Biochemical Oxygen Demand over five days (BOD_5), and suspended solids, pose a serious environmental threat if released untreated, particularly to aquatic environments.

In this context, the use of biological treatment processes, especially fixed-film systems, represents a viable and efficient solution. These systems promote the development of microbial biofilms attached to an inert support, allowing for the biological degradation of organic pollutants. Compared to conventional activated sludge systems, fixed-film reactors offer several advantages, including improved hydraulic and biological stability, compact design, lower sludge production, and ease of operation.

This research project falls within that framework and aims to experimentally assess the performance of a fixed-film biological reactor in treating synthetic dairy wastewater. The main objective is to evaluate the influence of key operational parameters—particularly the influent flow rate, biofilm dynamics, and physicochemical variations of the effluent—on treatment efficiency, expressed through the removal of COD, BOD_5, and mass removal rates.

To present the work conducted, the following chapters are proposed:

- The first chapter provides a literature review on the sources and characteristics of dairy industry wastewater, its environmental impact, and conventional treatment methods.
- The second chapter focuses on biological treatment processes, with special emphasis on fixed-film systems—their principles, classifications, benefits, and limitations.
- The third chapter presents the experimental methodology, a detailed description of the reactor used, the monitored parameters, as well as the analysis and discussion of the obtained results.

The thesis concludes with a general conclusion summarizing the experimental findings and offering perspectives for future research, with a view to optimizing and scaling up this treatment solution for real-world dairy effluent management.

Chapter I

Fundamentals of wastewater characterization and treatment technologies

I.1 Definition and origin of wastewater

Wastewater refers to water that has been polluted through human use whether domestic, industrial, or agricultural (Eaufrance, 2021). It includes blackwater (from toilets) and greywater (from sinks, showers, kitchens), as well as effluents from industrial or agri-food activities and urban runoff (Gazettes Africa, 2022; Eaufrance, 2021). Blackwater typically carries a high organic load and pathogenic microorganisms, while greywater contains fats, detergents, and various organic compounds. Industrial wastewater may contain effluents rich in specific chemical contaminants, such as pesticides, solvents, and heavy metals (Eaufrance, 2021). Even rainwater and infiltrated groundwater can become classified as wastewater when they are contaminated by roadway or agricultural pollutants. Therefore, discharging any of these waters into the natural environment requires proper treatment and sanitation to avoid ecological and health risks (Eaufrance, 2021).

I.2 Characteristics of wastewater

I.2.1 Physical parameters

I. 2.1.1 Temperature

Temperature is a critical physical parameter in wastewater, as it influences the rate and efficiency of chemical and biological reactions. Accurate measurement is essential because microbial activity and oxygen solubility are both temperature-dependent (Metcalf & Eddy, 2014).

I. 2.1.2 Suspended Solids (SS)

Suspended solids refer to undissolved particles greater than 10 µm present in water, which contribute to turbidity and are a key indicator of particulate pollution. Volatile Suspended Solids (VSS) are the biodegradable fraction of total suspended solids and are crucial for biological treatment processes (Tchobanoglous et al., 2003).

I. 2.1.3 Turbidity

Turbidity measures the cloudiness or opacity of water caused by fine suspended materials such as clay, silt, and organic matter. It reduces water clarity and can interfere with light penetration, affecting photosynthesis and aquatic life (Spellman, 2017).

I. 2.1.4 Color

Water color can serve as an indicator of pollution: darker water typically suggests contamination by organic matter or industrial discharges, whereas clear water is often less polluted (Metcalf & Eddy, 2014).

I. 2.2 Chemical parameters

I. 2.2.1 pH

pH indicates the acidity, neutrality, or alkalinity of a solution. It is a vital parameter because most aquatic organisms thrive in a narrow pH range and many treatment processes depend on maintaining proper pH levels (Tchobanoglous et al., 2003).

I. 2.2.2 Electrical conductivity

Conductivity measures the ability of water to conduct electrical current, which is directly related to the concentration of dissolved salts (ions). It is often used as an indicator of mineral content or pollution (Spellman, 2017).

I. 2.2.3 Dissolved Oxygen (DO)

Dissolved oxygen is crucial for aquatic life and plays a key role in aerobic biological processes. Low DO levels may indicate high organic load or pollution and can lead to anaerobic conditions harmful to ecosystems (UNESCO, 2017).

I. 2.2.4 Chemical Oxygen Demand (COD)

COD represents the total amount of oxygen required to chemically oxidize organic and inorganic substances in water using a strong oxidant. It provides an estimate of potential pollution even from non-biodegradable substances (Metcalf & Eddy, 2014).

I. 2.2.5 Biochemical Oxygen Demand (BOD_5)

BOD_5 is the amount of oxygen consumed by microorganisms during the degradation of organic matter over five days at 20°C. It reflects the biodegradable fraction of organic pollution (Tchobanoglous et al., 2003). The higher the BOD, the more polluted the water is with biodegradable material.

I. 2.2. 2 Nitrogen

Nitrogen in wastewater can be organic (proteins, urea) or inorganic (ammonia, nitrites, nitrates). Inorganic forms usually dominate and are critical to monitor due to their role in eutrophication and toxicity (Spellman, 2017).

I. 2.2.7 Phosphorus

Phosphorus typically originates from detergents and industrial products. It contributes significantly to eutrophication and algal blooms when discharged untreated into surface waters (UNESCO, 2017).

I. 2.3 Bacteriological parameters

Bacteria are naturally present in water, but some species are pathogenic to humans. Wastewater contains a variety of microorganisms, including coliforms, E. coli, Salmonella, and others that must be reduced through effective treatment to ensure public health safety (WHO, 2015).

I.3 Biodegradability concept

Biodegradability is the capacity of a wastewater effluent to be broken down by microorganisms in biological treatment systems. It is often evaluated using the ratio of COD to BOD_5.

$$K = \frac{COD}{BOD_5}$$ (Tchobanoglous et al., 2003).

- If K < 1.5, the effluent is considered biodegradable
- If 1.5 < K < 2.5, it is moderately biodegradable
- If K > 2.5, the effluent is non-biodegradable, likely containing inhibitory substances or recalcitrant compounds.

I.4 Wastewater discharge standards in Algeria

Algerian environmental regulations establish strict discharge limits for wastewater to safeguard both public health and aquatic ecosystems (CNTTP, 2023). These standards are enforced through national legislation and target critical physical, chemical, and bacteriological parameters in treated effluents. Table I.1 outlines the principal permissible limits.

Table I.1: Key maximum allowable values for wastewater discharges in Algeria (CNTTP, 2023).

Parameter	Limit value
pH	6.5–8.5
Temperature	≤ 30 °C
COD (Chemical Oxygen Demand)	≤ 35 mg/L
BOD_5 (Biochemical Oxygen Demand)	≤ 30 mg/L
Arsenic	≤ 1.0 mg/L
Hexavalent Chromium	≤ 0.10 mg/L
Trivalent Chromium	≤ 0.05 mg/L
Silver	≤ 0.05 mg/L
Chlorinated Solvents	0 mg/L
Fecal Streptococci	≤ 1,000 per 100 mL
Fecal Coliforms	≤ 2,000 per 100 mL
Salmonella & Cholera Vibrio	0 in 5,000 mL

These thresholds reflect Algeria's efforts to harmonize with international wastewater management practices and reduce the toxicological and ecological impacts of effluent discharges. They also serve as a framework for industrial compliance and environmental monitoring throughout the country (CNTTP, 2023).

I.5 Wastewater treatment: The standard stages of purification

Effective wastewater treatment is essential for public health and environmental protection, particularly in water-scarce regions like Algeria, where untreated discharges can lead to disease outbreaks and ecological degradation (Adeniyi et al., 2024; Aissaoui et al., 2022). Elevated levels of organic matter and nutrients in untreated effluents reduce dissolved oxygen in water bodies, causing eutrophication, harmful algal blooms, and a decline in aquatic biodiversity (Adeniyi et al., 2024). The presence of pathogens and emerging contaminants, such as microplastics and pharmaceuticals, further threatens ecosystem and community health.

Given Algeria's growing water scarcity, the reuse of treated wastewater and by-products like nutrient-rich sludge and biogas is increasingly important for irrigation, aquifer recharge, and sustainable resource management (Bouanani et al., 2020; Adeniyi et al., 2024). However, challenges persist due to aging infrastructure and inconsistent treatment standards, which can result in incomplete removal of contaminants such as surfactants, pharmaceuticals, and micro plastics (Ahmia et al., 2016; Adeniyi et al., 2024).

To address these issues and support sustainability goals, wastewater is processed through a series of standardized purification stages. Each stage-from preliminary screening and grit removal to advanced biological, chemical, and disinfection processes-targets specific pollutants, ensuring the elimination of solids, organic matter, nutrients, pathogens, and emerging micro contaminants. Mastery of these stages is crucial for designing treatment systems that are efficient, resilient, and environmentally responsible.

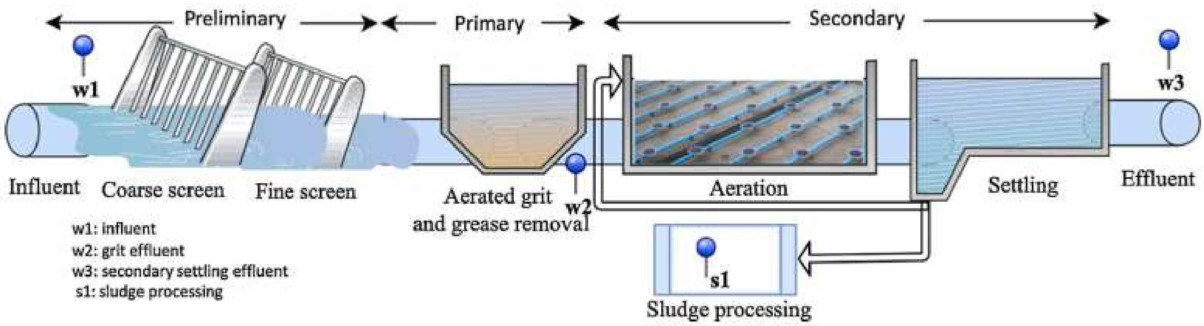


Figure I.1: The standard stages of wastewater treatment.

I.5.1 Preliminary treatment

Preliminary treatment involves three main steps to remove materials that could hinder subsequent treatment phases. Not all treatment plants implement all three steps; however, screening is commonly used, while grit removal and oil removal are applied as needed.

I.5.1.1 Screening and Sieving

This step removes insoluble waste such as branches, plastics, and sanitary products. Wastewater passes through one or more screens with progressively finer meshes, often equipped with automatic cleaning systems to prevent clogging and protect downstream equipment.

I.5.1.2 Grit removal

Through sedimentation, this process eliminates sand and grit introduced by runoff or pipe erosion. Removing these materials prevents equipment wear and operational issues. Extracted grit may be washed before disposal to reduce organic content and associated odors.

I.5.1.3 Oil and grease removal

Typically using dissolved air flotation, fine air bubbles are injected into the tank, causing hydrophobic fats to rise to the surface for removal. This step is crucial to prevent downstream clogging and maintain treatment efficiency.

Often, grit and oil removal occur in the same tank, with slow water movement allowing sand to settle and grease to float.

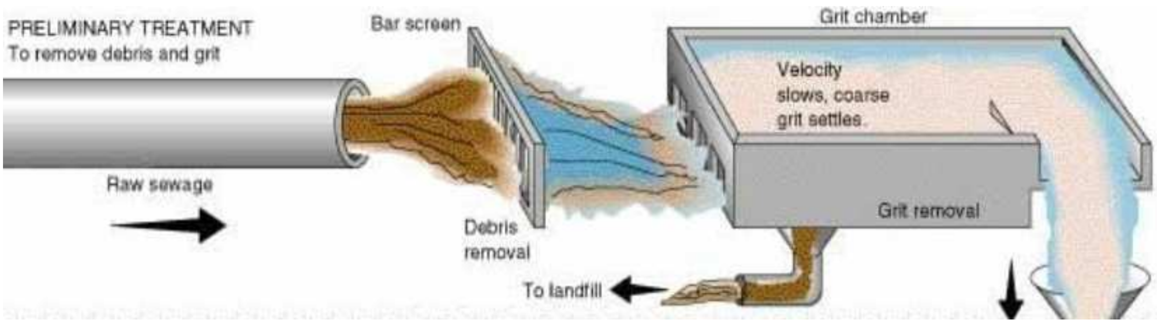


Figure I.2: Preliminary treatment.

I.5.2 Primary treatment

Primary treatment involves simple sedimentation to remove the majority of suspended solids, which cause water turbidity. This process occurs in sedimentation basins, where the retention time depends on the volume and type of wastewater. The effectiveness of sedimentation is measured by the Mohlman index, monitored daily in major treatment plants.

This stage removes approximately 60% of suspended solids, 30% of biochemical oxygen demand (BOD), and 30% of chemical oxygen demand (COD). The settled solids form "primary sludge" at the bottom of the tank. In some regions, primary treatment is being phased out in favor of secondary treatment methods that include sedimentation steps.

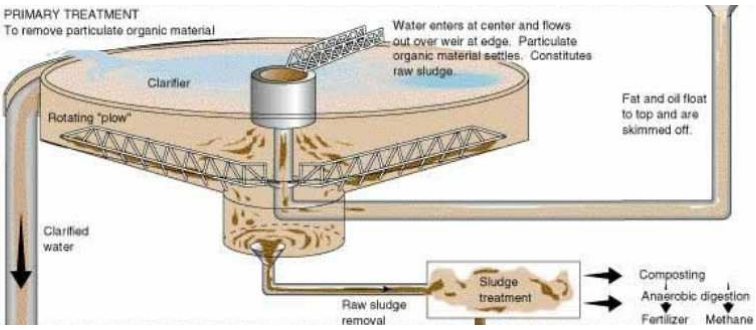


Figure I.3: Primary treatment (Primary sedimentation).

I.5.3 Secondary treatment

Secondary treatment constitutes a vital phase in the wastewater treatment process, primarily relying on biological mechanisms to eliminate dissolved organic matter and nutrients. When necessary, physical-chemical methods may be incorporated to improve flocculation, coagulation, or phosphorus removal, thereby enhancing the overall efficiency of the treatment process.

I.5.3.1 Biological treatment

Biological treatment is a foundational element of contemporary wastewater management, utilizing the metabolic activity of microorganisms to break down biodegradable organic compounds and remove nutrients, especially nitrogen-based pollutants (Tchobanoglous et al., 2013). Due to their high removal efficiency**,** scalability, and environmental benefits, biological processes are extensively used in municipal and industrial wastewater treatment plants. These processes are typically categorized into two main types based on their oxygen requirements: aerobic and anaerobic systems.

a) Aerobic processes

Aerobic systems function in the presence of dissolved oxygen, allowing microorganisms to oxidize organic matter into carbon dioxide, water, and additional biomass. Common technologies include activated sludge systems, biofilters, and moving bed biofilm reactors (MBBRs). These systems are highly effective at reducing chemical oxygen demand (COD) and biochemical oxygen demand (BOD), often achieving removal rates greater than 90% under optimal operational conditions (PubMed, 2019; Semantic Scholar, 2022). However, aerobic systems are energy-intensive due to aeration requirements and tend to produce significant volumes of excess sludge.

b) Anaerobic processes

Anaerobic processes occur in oxygen-free environments, where specialized microorganisms convert complex organic matter into biogas, primarily composed of methane and carbon dioxide. This biogas can be recovered and used as a renewable energy source (Oryx Eleven, 2022). Anaerobic treatment is especially effective for high-strength industrial wastewater, and its low energy demand makes it economically attractive. Although COD removal in anaerobic systems generally reaches up to 90%, the integration of anaerobic and aerobic processes can enhance overall treatment efficiency and cost-effectiveness (PubMed, 2019; Semantic Scholar, 2019).

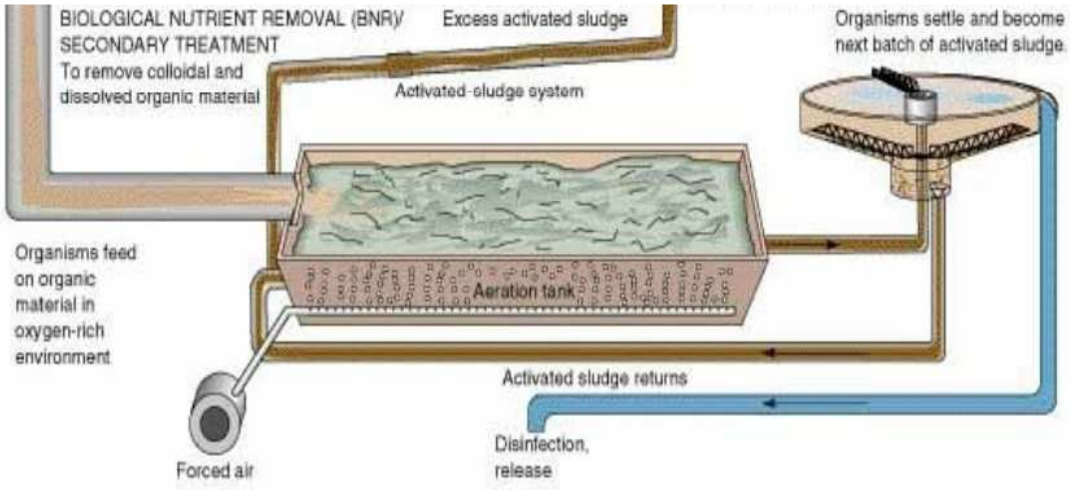


Figure I.4: Secondary treatment (Activated sludge process).

I.5.3.2 Physical-chemical treatment

Physical-chemical treatment is an essential complement to biological processes in secondary wastewater treatment, targeting the removal of fine suspended and dissolved pollutants that are not fully addressed by biological means. This stage commonly involves aeration, mixing, and secondary sedimentation (clarification). After clarification, the treated water may either be discharged or sent to tertiary treatment, while most of the settled sludge is recycled to the aeration basin, with the surplus directed to storage or further processing. Integrating physical-chemical methods-such as enhanced flocculation, coagulation, and phosphorus removal-significantly improves the overall effectiveness of the treatment process.

- **Physico-chemical sedimentation**

Water turbidity and coloration are often caused by fine colloidal particles that remain suspended and do not settle naturally. To remove these, two main steps are used:

1) Coagulation: This involves the rapid addition and dispersion of chemicals (such as iron or aluminum salts) to neutralize the electrical charges on colloids, causing them to aggregate into microflocs.

2) Flocculation: Gentle mixing then encourages these microflocs to form larger flocs, which settle out by gravity during sedimentation, resulting in clearer water.

- **Phosphorus removal**

Phosphorus is a key contributor to eutrophication, so its removal is crucial for environmental protection. Several strategies are employed:

1. Physical methods: Filtration or membrane processes physically separate phosphorus from the water.
2. Chemical methods: Addition of specific chemicals precipitates phosphorus into insoluble compounds that can be removed.
3. Combined physical-chemical methods: Integrating filtration and chemical precipitation enhances removal efficiency.
4. Biological removal (EBPR): Certain microorganisms, especially under alternating anaerobic and aerobic conditions, can accumulate phosphorus intracellularly.
5. Mixed treatments: Combining biological and chemical processes is often necessary to meet stringent discharge requirements.

Ongoing research is focused on developing more efficient and sustainable phosphorus removal technologies, including the use of biopolymers, bioinspired materials, and advanced adsorption techniques. These innovations aim to improve removal rates, reduce environmental impact, and recover phosphorus as a valuable resource.

This approach ensures that secondary treatment not only meets regulatory standards for pollutant removal but also supports broader goals of resource recovery and environmental sustainability.

I.5.4 Tertiary treatment

Tertiary treatment enhances the removal of suspended solids, phosphorus, and pathogens, particularly in sensitive receiving environments.

- Suspended solids and organic matter: Additional sedimentation via flocculation with polymers or coagulants, and filtration through micro, ultra, or nanofilters, further purify the water.
- Nitrogen and Phosphorus: Advanced treatments target residual nitrogen and phosphorus, using chemical precipitation or biological assimilation methods.
- Bacteriological treatment: To reduce pathogenic bacteria, disinfection methods such as chlorination, ozonation, ultraviolet (UV) irradiation, or sand filtration are employed, especially when protecting bathing waters or drinking water sources.
- UV Disinfection: Various systems expose water to UV light, effectively reducing microbial content without chemical additives.

- Physical-chemical treatment: Includes disinfection with chlorine or ozone and neutralization of dissolved metals through pH adjustments.
- Alternative or extensive processes: Natural lagoon systems or vertical flow systems with microalgae cultures offer sustainable options for small-scale or decentralized wastewater treatment.

I.5.5 Quaternary treatment: micropollutant removal

Traditional treatment stages may not eliminate micropollutants—trace compounds like pharmaceutical residues, hormones, pesticides, and cosmetics—that can harm aquatic life even at low concentrations.

Advanced oxidation processes (AOPs), such as the Fenton reaction using hydroxyl radicals, effectively degrade these persistent pollutants into harmless end products. In Switzerland, regulations mandate the removal of at least 80% of micropollutants, leading to the adoption of methods like activated carbon adsorption and ozonation.

I.5.6 Sludge treatment

Sludge, the primary byproduct of wastewater treatment, undergoes several processes to reduce volume and environmental impact:

- Dewatering: Techniques like centrifugation, filter pressing, and drying beds reduce water content, facilitating disposal or further treatment.
- Incineration or landfilling: Depending on toxicity, sludge may be incinerated or disposed of in landfills.
- Biogas production: Anaerobic digestion of sludge produces methane-rich biogas, which can be harnessed for energy.

I.5.7 Challenges

Wastewater treatment faces several operational challenges:

- Treatment malfunctions: Issues like sludge bulking, often caused by filamentous bacteria such as *Microthrix parvicella*, can disrupt sedimentation processes. Factors include sudden organic load increases and the presence of inhibitory substances.
- Sludge valorization difficulties: Finding sustainable applications for certain sludge types remains challenging, leading to increased reliance on disposal methods.
- Odor management: Odors from sludge and pumping stations can be mitigated through:
  - Physico-chemical treatments: Chemical scrubbing systems achieve high odor removal efficiencies by transferring odorous compounds into aqueous solutions.
  - Biological treatments: Biofiltres use microorganisms to degrade odorous compounds, requiring optimal humidity and nutrient conditions.

- Activated carbon adsorption: Odorous molecules are captured on activated carbon surfaces, effectively reducing emissions.

I.6 Overview of biological wastewater treatment processes

Biological wastewater treatment processes are typically divided into two primary categories according to the microbial habitat and operational principles: suspended growth systems (free culture) and attached growth systems (fixed culture) (see Figure I.5).

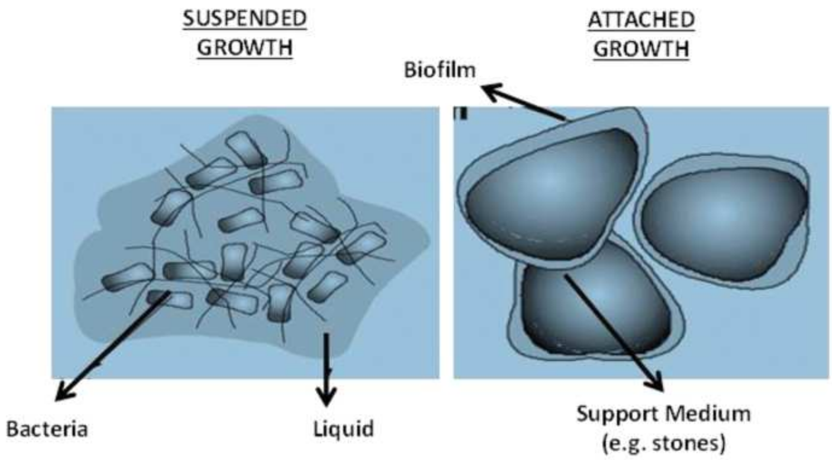


Figure I.5: Types of biological wastewater treatment systems (von Sperling, 2007).

I.6.1 Suspended growth systems (Free culture)

In suspended growth systems, microorganisms remain in suspension within the liquid phase. These systems provide high flexibility and responsiveness to fluctuations in pollutant load. Examples include activated sludge systems and waste stabilization ponds, where microbes are suspended throughout the liquid phase

I.6.1.1 Activated sludge process

The activated sludge process is a widely employed biological wastewater treatment method that relies on the principle of suspended microbial biomass. In this system, pre-treated wastewater is introduced into an aeration basin, where a diverse microbial community—primarily aerobic bacteria—develops and remains suspended in the mixed liquor. These microorganisms metabolize and degrade dissolved organic pollutants and, under controlled aerobic and anoxic conditions, perform nitrification and denitrification, allowing for the removal of nitrogen compounds such as ammonium and nitrate.

After the biological treatment stage, the mixed liquor flows into a secondary clarifier, where gravity sedimentation separates the treated water from the activated sludge. A portion of the sludge is recycled back to the aeration basin to maintain microbial activity, while excess sludge is removed for further processing and disposal.

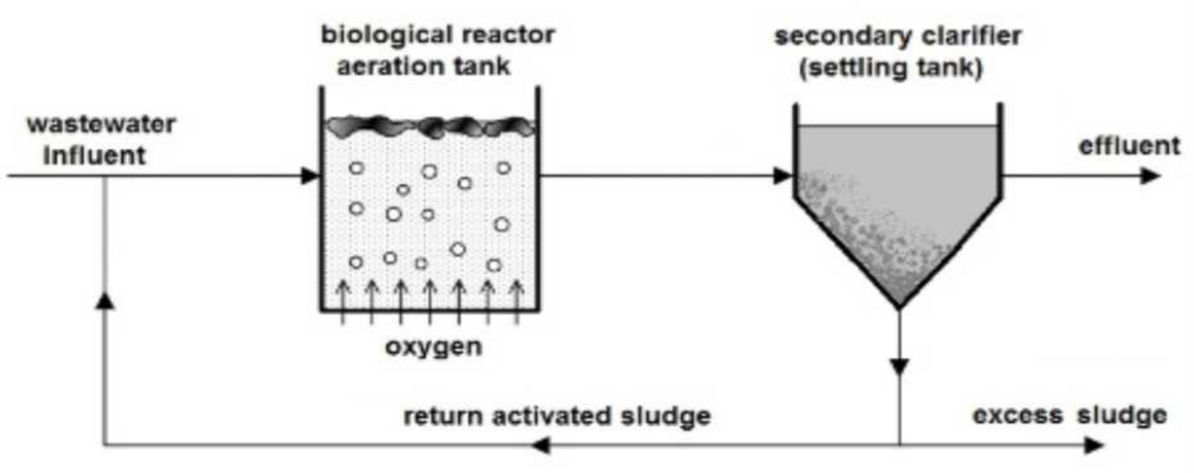


Figure I.6: principle of the activated sludge water treatment process (Frącz, P., 2016).

This process is known for its high treatment efficiency, particularly in terms of organic load and nutrient removal, and is widely applied in municipal wastewater treatment plants and in industries dealing with biodegradable effluents.

I.6.1.2 Waste stabilization ponds (Lagoons)

Waste stabilization ponds (WSPs), also termed lagoon systems, are extensive biological treatment systems that utilize natural processes to purify wastewater in large, shallow basins. These systems rely on symbiotic interactions between algae and bacteria: algae generate oxygen via photosynthesis, which aerobic bacteria then use to biodegrade organic matter, reducing pollutant concentrations (Shilton, 2021).

WSPs are ideal for small communities and rural areas due to their simplicity, low operational costs, and minimal mechanical requirements (Mara, 2021). However, their efficiency depends heavily on climatic factors (e.g., temperature, sunlight) and requires significant land area (von Sperling, 2021). Historically, natural or artificial ponds have been used for wastewater management for centuries, but modern lagoon systems emerged in the early 20th century (Kayombo et al., 2021).

Two primary types of lagoons are recognized:

- Natural lagoons: These include anaerobic, facultative, or aerobic configurations, depending on depth, retention time, and oxygen levels. When used for polishing treated effluent, they are termed stabilization ponds (Mara, 2021).
- Aerated lagoons: These incorporate mechanical aerators to boost oxygen levels, enabling controlled biological activity. Their operation resembles low-rate activated sludge systems but offers simpler infrastructure and greater resilience to load fluctuations (Shilton, 2021).

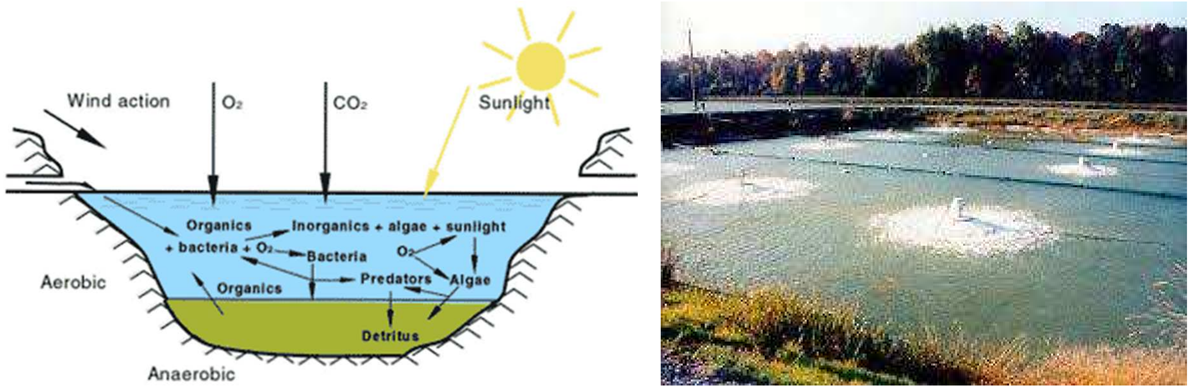


Figure I.7: Waste stabilization pond treatment (Natural and aerated lagoon).

WSPs remain a practical solution for decentralized treatment, particularly in developing regions with ample land and favorable climates (Kayombo et al., 2021). Studies demonstrate that modifications like baffles or fixed media can enhance performance; for example, baffled facultative lagoons achieved 83% coliform removal compared to 67% in unbaffled systems (Almasi et al., 2017).

I.6.2 Attached growth systems

In fixed culture systems, microorganisms form biofilms that adhere to inert support surfaces. This configuration offers greater robustness against load variations and enhanced resistance to toxic shocks. Examples include trickling filters, rotating biological contactors (RBCs), and submerged biofilters, where microbes grow on media and treat water as it flows past.

I.6.2.1 Trickling filters

Trickling filters are aerobic biological treatment systems that utilize microbial biofilms growing on a fixed support medium to degrade organic matter in wastewater. In these systems, wastewater is evenly distributed over a bed of materials-such as stones or plastic media-on which biofilms develop (Figure I.8). These microbial communities facilitate the oxidation of organic pollutants, converting them into carbon dioxide, water, and additional biomass (Grady et al., 2011).

The performance of trickling filters is influenced by several operational factors. They are characterized by short hydraulic retention times, often just a few minutes, and exhibit strong resilience to fluctuations in both organic and hydraulic loading. However, excessive biomass accumulation can lead to clogging, which remains a significant operational challenge (Ahmad et al., 2024).

Trickling filters are widely recognized for their reliability across various wastewater treatment applications, particularly as tertiary treatment units. They consistently achieve high and stable rates of nitrification-often exceeding 90%-even under variable loading conditions, especially when mechanical aeration is incorporated (Kumar et al., 2024). Their adaptability is further demonstrated in diverse climates: in alpine regions, adaptive recirculation strategies help maintain treatment efficiency despite seasonal changes (Grady et al., 2011), while in tropical environments, trickling filters have achieved up to 76.7% BOD_5 removal, outperforming sequencing batch reactors due to their operational simplicity and robustness (Ahmad et al., 2024).

Figure I.8: Trickling filter (Wikipedia contributors, n.d.).

From an operational perspective, trickling filters are notably resilient, capable of quickly resuming normal performance after short interruptions, such as 24-hour shutdowns. However, prolonged inactivity-exceeding 52 days-can significantly reduce their effectiveness and result in non-compliance with discharge standards (Kumar et al., 2024). To address clogging, the use of high-surface-area media like expanded polystyrene (EPS) or routine system flushing has proven effective (Semblano et al., 2023; Shahi et al., 2007). Additionally, implementing thermal insulation or adjusting hydraulic loading can help mitigate efficiency losses during colder periods, and the use of locally available plastic waste as filter media can reduce material transport costs (Ahmad et al., 2024).

I.6.2.2 Rotating biological contactors (RBCs)

Rotating Biological Contactors (RBCs), also referred to as biodiscs, are commonly used attached-growth systems for municipal and industrial wastewater treatment. As described by Ahmad et al. (2023), an RBC system consists of a series of closely spaced discs-typically made from composite or plastic materials-mounted on a horizontal shaft, with each disc partially submerged (40–60%) in wastewater and rotating at 1 to 6 revolutions per minute. This rotation alternately exposes the biofilm on the disc surfaces to wastewater and atmospheric oxygen, facilitating oxygen transfer and substrate uptake by aerobic microorganisms.

The alternating exposure supports a diverse microbial community, enabling efficient degradation of organic matter and conversion of nitrogenous compounds through nitrification and, under certain conditions, denitrification (Ahmad et al., 2023). Studies have reported that RBCs can achieve chemical oxygen demand (COD) removal rates between 85–94% and ammonium removal rates exceeding 95% when optimal hydraulic retention times and loading conditions are maintained (Kumar et al., 2021).

Figure I.9 : Biodisks.

RBCs offer several operational advantages, including simple operation, low energy consumption due to slow disc rotation, and compact design, making them suitable for decentralized or medium-sized treatment plants (Rahman et al., 2022). However, their performance depends on factors such as rotational speed, submergence depth, hydraulic retention time, and loading rates, with excessive loading potentially leading to biofilm sloughing and reduced effluent quality (Ahmad et al., 2023). Temperature also significantly affects microbial activity and system efficiency.

Recent advances include integrating RBCs with membrane filtration or algal-bacterial consortia to enhance effluent quality and nutrient removal (Rahman et al., 2022). Despite their advantages, RBCs face challenges such as biofilm detachment, mechanical wear, and sensitivity to extreme operational conditions, requiring regular maintenance and careful control (Ahmad et al., 2023).

I.6.2.3 Submerged biofilters

Submerged biofilters are compact, fixed-bed biological systems that combine physical filtration and microbial degradation to treat wastewater (see Figure I.10). These systems utilize inert media (e.g., zeolite, activated carbon) fully submerged in water to support biofilm growth, making them effective for high-strength wastewater in space-limited installations (Cárdenas et al., 2020).

Figure I.10: Typical submerged media reactor.

The process relies on a gas-liquid-solid interaction where biofilms degrade organic compounds and filter suspended solids (SS). The biofilm's heterogeneous structure enhances stability against hydraulic fluctuations compared to suspended-growth systems like activated sludge (Zhang et al., 2010). Upflow configurations are preferred for superior retention and efficient air-water distribution (see Figure I.11), particularly in treating domestic sewage with high ammonium concentrations (Jóźwiakowski et al., 2017). Downflow systems are less common and typically reserved for industrial applications (Hai et al., 2017).

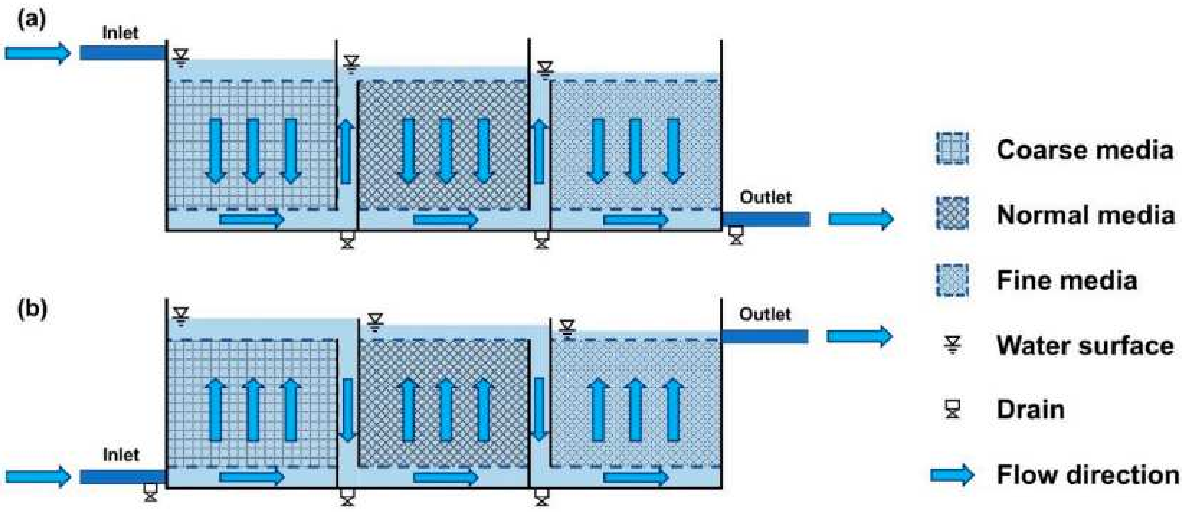


Figure I.11: Schematics submerged filters: (a) down-flow roughing filter, and (b) up-flow roughing filter (Kim et al., 2020).

Media selection critically influences performance. Materials such as granular coal, expanded polystyrene, and zeolite are chosen for their high surface area (200–1,000 m^2/m^3), void fraction, and granulometry (2.2–4.5 mm) to balance microbial colonization and clogging prevention (Cárdenas et al., 2020). Aerobic submerged biofilters achieve 76–95% BOD_5 removal, while anaerobic variants remove 62–68% COD (Chen et al., 2014; Jóźwiakowski et al., 2017). Hybrid systems, like combined upflow anaerobic sludge bed (UASB) and biofilters, reach 83.6% COD and 41.2% nitrogen removal in swine wastewater (Chen et al., 2014).

These systems are ideal for decentralized rural treatment due to low energy use and operational simplicity (Jóźwiakowski et al., 2017). They also treat industrial effluents, including dairy and paper mill wastewater (Hai et al., 2017). Innovations like sequencing batch biofilter granular reactors (SBBGRs) enhance nutrient removal and sludge stability through microbial consortia dominated by *Amoebacteria* and *Bacteroides* (Liu et al., 2023).

Challenges include clogging, mitigated via backwashing and high-void media, and sensitivity to temperature shifts or shock loads (Hai et al., 2017). Despite material costs (e.g., granular coal constituting 23% of installation expenses), long-term cost-effectiveness remains favorable (Cárdenas et al., 2020).

Chapter II

Design concepts and performance criteria of trickling filters

II.1 Operating principle of trickling filters

Trickling filters function as an attached-growth aerobic biological treatment process, where microorganisms colonize the surfaces of filter media and develop into a biofilm, instead of remaining suspended in the liquid phase (U.S. Environmental Protection Agency [EPA], 2000). As wastewater flows downward by gravity through the filter bed, the biofilm actively degrades organic contaminants, transforming them into carbon dioxide, water, and new microbial biomass (Suez Water Technologies, n.d.). This section provides an overview of the fundamental operating principles, main structural elements, biofilm dynamics, and essential operational practices associated with trickling filter technology.

II.1.1 Structural components and flow dynamics

As illustrated in Figure II.1, a conventional trickling filter consists of several essential components: (i) an influent pipe connected to a rotary distributor that ensures even distribution of wastewater over the filter bed; (ii) a cylindrical tank or enclosure; (iii) a packed bed of filter media, such as rock or plastic modules; (iv) an under-drain system designed to facilitate both effluent collection and aeration; and (v) an outlet for discharging the treated water (Great Lakes–Upper Mississippi River Board, 2004).

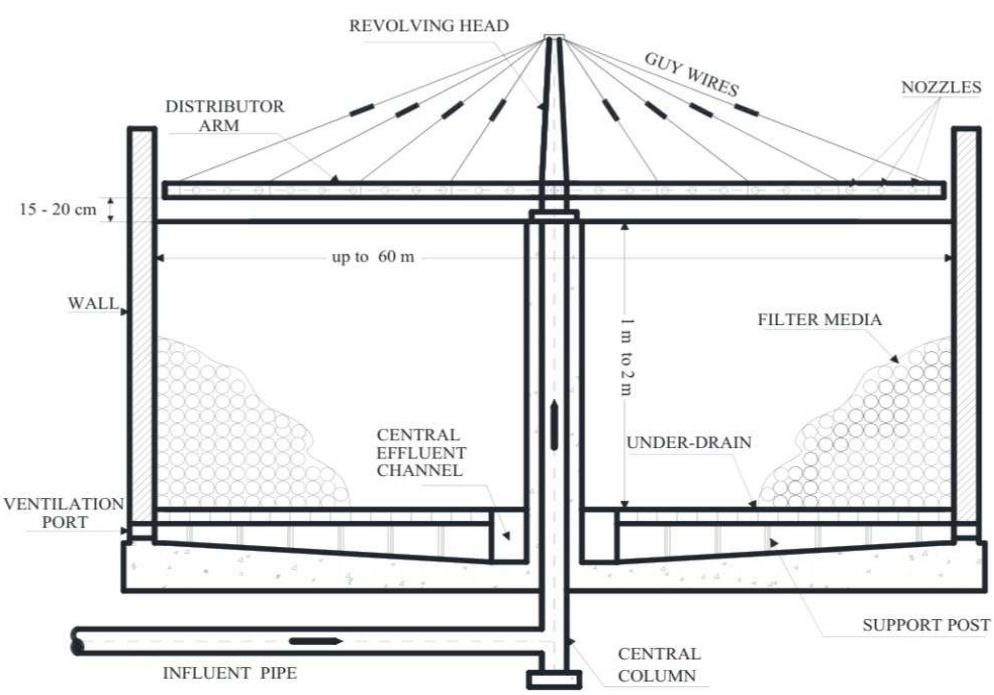


Figure II.1: Schematic cross-section of a conventional trickling filter system.

The rotary distributor arms, fitted with spray nozzles, rotate by means of hydraulic reaction forces, thereby guaranteeing uniform application of wastewater across the surface of the media bed. Such uniform loading is critical to prevent localized overgrowth of the biofilm, which can result in clogging and reduced system efficiency (Florida Department of Environmental Protection [DEP], 2004). To ensure unobstructed operation, the distributor is typically positioned with a minimum clearance of 0.3 meters above the media surface.

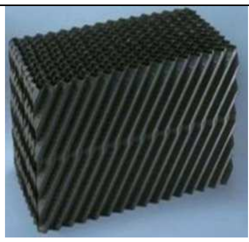
II.1.2 Filter media

The filter media, typically composed of crushed stone (50–100 mm) or structured plastic, serves as a substrate for microbial colonization, offering a high specific surface area (>90 m^2/m^3) and substantial void space to support biofilm growth and airflow (Suez Water Technologies, n.d.). As wastewater flows over the media, it hydrates the biofilm, which consists of aerobic heterotrophs, nitrifying bacteria, and protozoa. These microorganisms oxidize biodegradable organic matter, quantified as 5-day Biochemical Oxygen Demand (BOD_5), and under optimal conditions, facilitate nitrification (U.S. Environmental Protection Agency [EPA], 2000).

Biofilm thickness increases progressively, creating anaerobic inner layers due to limited oxygen diffusion. As nutrient and oxygen availability declines, microbial cells undergo endogenous decay and detach from the media-a self-renewal mechanism vital for maintaining filter efficiency (NPTEL, 2014). Table II.1 summarizes key physical properties of common trickling filter media.

Table II.1: Properties of selected trickling filter media (U.S. Environmental Protection Agency [EPA], 2000).

Media Type	Material	Nominal Size (m)	Bulk Density (kg/m^3)	Specific Surface Area (m^2/m^3)	Void Space (%)
River Rock		0.024 – 0.076	1442	62	50
Slag		0.076 – 0.128	1600	46	60

Cross Flow	 PVC	0.61 × 0.61 × 1.22	384 – 721	100 and 223	95
Vertical Flow	 PVC	0.61 × 0.61 × 1.22	384 – 721	102 and 131	95
Random Packing	 Polypropylene	0.185 (D) × 0.051(H)	432	98	95

II.1.3 Airflow and oxygenation

Adequate ventilation is crucial for supporting the aerobic metabolism within the trickling filter. Most systems are passively aerated through natural convection; air enters via vents at the base of the filter and flows upward as water trickles downward (U.S. EPA, 2000). This "chimney effect" ensures sustained oxygen transfer throughout the biofilm. The under-drain system is designed to facilitate both effluent drainage and air circulation, maintaining aerobic conditions within the media. In colder climates or enclosed systems, forced aeration may be necessary (Great Lakes–Upper Mississippi River Board, 2004).

II.1.4 Under-drain system and effluent removal

The under-drain system consists of perforated channels that are sloped slightly toward a central or peripheral outlet. This system collects the treated effluent and any sloughed biomass, directing them to a subsequent settling tank, often called a clarifier. In the clarifier, solids are removed, and the clarified water can then be discharged or undergo further treatment (Suez Water Technologies, n.d.). Proper hydraulic design of these channels is important to ensure they remain free-flowing and open for air movement (Florida DEP, 2004).

II.1.5 Operational considerations

Effluent recirculation is a common operational strategy used to stabilize loading conditions and maintain biofilm wetness, particularly during periods of low influent flow. Recirculation ratios typically range from 0.5:1 to 4:1 (U.S. EPA, 2000). Routine maintenance activities include cleaning distributor nozzles, checking biofilm thickness, inspecting under-drains, and monitoring for potential filter fly infestations. To control excessive biomass buildup or to clean the filter, temporary measures such as flooding or high-rate dosing may be employed (Florida DEP, 2004).

II.2 Classification of trickling filters

Various classification schemes are used to differentiate trickling filters based on applied organic and hydraulic load, type of packing media, and intended treatment objective.

II.2.1 Definitions

Organic load refers to the quantity of biodegradable organic matter entering a wastewater treatment system per unit volume and time, typically measured as biochemical oxygen demand (BOD) or chemical oxygen demand (COD). This parameter determines the biological treatment capacity required to degrade pollutants effectively. It is expressed as mass per unit time (e.g., kilograms of BOD per day [kg BOD/day]) or mass per unit volume per unit time (e.g., grams of BOD per cubic meter per day [g BOD/m³/day]) (Tchobanoglous et al., 2014). The organic load is calculated as:

$$B_{V,BOD} = \frac{Q_{average} \times L_0}{V}$$

Where**:**

$B_{V,BOD}$: Organic load per bed volume (kg BOD_5/m³/day)

$Q_{average}$: Daily average wastewater flow rate (m³/day)

L_0: Influent BOD_5 concentration (kg/m³)

V: Trickling filter bed volume (m³)

Hydraulic load refers to the volume of wastewater flowing through a treatment system over a specific period, influencing the contact time between wastewater and treatment media. It is expressed as flow rate (e.g., cubic meters per day [m³/day]) or flow per unit area (e.g., cubic meters per square meter per day [m³/m²/day]) in surface-loaded systems such as trickling filters (Metcalf & Eddy, 2014). The hydraulic load is calculated as:

$$HLR = \frac{Q_{TF}}{A}$$

Where:

HLR: Surface hydraulic loading rate (m/hour)

Q_{TF}: Flow rate applied to the trickling filter (m^3/hour), including recirculation

A: Horizontal surface area of the filter bed (m^2)

II.2.2 Classification by organic and hydraulic load

Historically, trickling filters have been categorized based on the organic and hydraulic loading rates applied to the system, which directly influence performance and application (EPA, 2000a).

II.2.2.1 Low-rate trickling filters

Low-rate trickling filters typically operate at organic loading rates of 0.1–0.4 kg BOD_5/m^3/day. They use conventional media such as gravel or pumice stone, with filter depths ranging from 1–2 meters. The extended contact time in these systems promotes high biochemical oxygen demand (BOD) removal and advanced ammonium nitrification under optimal conditions (SUEZ, n.d.; Baroud et al., 2018).

II.2.2.2 Intermediate-rate trickling filters

Intermediate-rate filters often employ two stacked stages and partial effluent recirculation. This design enhances biofilm hydration and minimizes clogging risks. Operating at medium organic loads (approximately 0.5–1 kg BOD_5/m^3/day), these systems achieve substantial carbon removal and partial nitrification (MELCC, 2021).

II.2.2.3 High-rate trickling filters

High-rate filters, also known as roughing or contact filters, are designed for high organic loads (>1 kg BOD_5/m^3/day). While they may not independently meet effluent standards, they are effective as pre-treatment stages before secondary processes. These filters are typically ventilated and energy-efficient, making them suitable for reducing primary pollution loads (EPA, 2000a; Baroud et al., 2018).

Hydraulic loading rates also play a critical role in classification. High-rate filters, for example, operate at hydraulic loading rates between 100–1,000 gallons per day per square foot, depending on the media type (DEP, n.d.; Water.mecc.edu, n.d.).

II.2.3 Classification by packing media and technology

The evolution of filter media has significantly impacted trickling filter performance and application.

II.2.3.1 Conventional media

Traditional trickling filters utilized mineral-based media such as crushed stone, coke, or scoria, with particle diameters of 2–10 cm and bed heights from 0.9 to 2.4 meters. These systems are generally circular, equipped with rotary distributors, and provide moderate specific surface areas (~150 m^2/m^3) (SUEZ, n.d.).

II.2.3.2 Modern plastic media

Contemporary trickling filters use high-performance plastic media, including honeycomb PVC and structured grids in vertical or crossflow configurations. These media enable the construction of bio-towers up to 12 meters in height and offer much higher specific surface areas (300–900 m^2/m^3), allowing for increased volumetric loads and improved efficiency (Baroud et al., 2018). Crossflow media (angled at 60°) enhance flow distribution in low-load conditions, while vertical flow media are preferred for high-load operations to reduce clogging risks (Baroud et al., 2018).

II.2.3.3 Advanced technologies

Some advanced systems incorporate forced aeration at the base of tall towers to maintain oxygen supply in deeper zones. At the technological frontier, fluidized bed reactors with suspended sand or plastic beads represent a departure from classic trickling filters, functioning as submerged biofilm systems.

II.2.4 Classification by treatment objective

Trickling filters are also classified according to their functional role in wastewater treatment:

II.2.4.1 Carbonaceous trickling filters

These filters are primarily designed for BOD and chemical oxygen demand (COD) removal following primary sedimentation. Low to intermediate-rate filters can remove 70–90% of BOD_5 through aerobic microbial degradation (EPA, 2000a).

II.2.4.2 Nitrifying trickling filters

Nitrifying filters target ammonia oxidation ($NH_4^+ \rightarrow NO_3^-$) after prior BOD removal. They operate under low organic loads to minimize competition from heterotrophic bacteria, utilizing high-surface-area plastic media and strong aeration to favor autotrophic nitrifiers such as Nitrosomonas and Nitrobacter (EPA, 2000b; Dorias & Baumann, 1994).

II.2.4.3 Combined trickling filters

Combined filters handle both carbon removal and partial nitrification. Low-rate filters can achieve some nitrification if oxygen is not depleted by BOD degradation. Complete nitrogen removal requires a separate denitrification step, often involving an anoxic zone and an external carbon source (MELCC, 2021). Effluent recirculation to an upstream filter containing residual BOD can enable partial in-situ denitrification in oxygen-limited biofilm zones (Baroud et al., 2018).

II.3 Matter conversion in trickling filters

The purification process in trickling filter systems relies on both biological and physicochemical mechanisms that convert pollutants into less harmful substances (Dubey & Kashyap, 2022). These mechanisms include biofilm formation, adsorption, oxygen and substrate transport, and matter transformation such as biodegradation, nitrification, and denitrification.

II.3.1 Biofilm formation

Biofilm formation begins as bacteria attach to the surface of the filter media and secrete extracellular polymeric substances (EPS), developing a protective matrix. This matrix enables bacteria to adhere, form structured communities, and resist antimicrobial agents. As the biofilm matures, additional bacteria join and EPS production continues, enhancing the biofilm's structure and providing a stable environment for microbial communities, which facilitates pollutant degradation (de M Muliyadi et al., 2024). A schematic representation of this process is provided in Figure II.2.

The biofilm develops at the interface between the support media and wastewater, forming the core of trickling filter operation (EPA, 2000). It consists mainly of heterotrophic and autotrophic bacteria, but also includes protozoa, microscopic fungi, and sometimes larger organisms such as rotifers and nematodes (SUEZ, n.d.). The EPS matrix forms a gelatinous layer that traps particulates and allows nutrients to diffuse throughout the community. The thickness of this layer can range from fractions of a millimeter to several millimeters, depending on factors such as organic load, temperature, and microbial activity.

Biofilm growth is self-regulated through sloughing. As the biofilm thickens-typically reaching 2–3 mm in mature systems-oxygen and substrate diffusion become limited in the deeper layers. Over time, aged or inactive zones develop, and internal layers depleted of oxygen detach due to hydraulic shear stress and gravitational forces (Filipkowska & Krzemieniewski, 1998; EPA, 2000). The sloughed material is carried away by the wastewater and removed in clarification units, making space for new microbial colonization and regeneration of active surfaces. This cycle ensures the continuous renewal and optimal functioning of the trickling filter system (EPA, 2000).

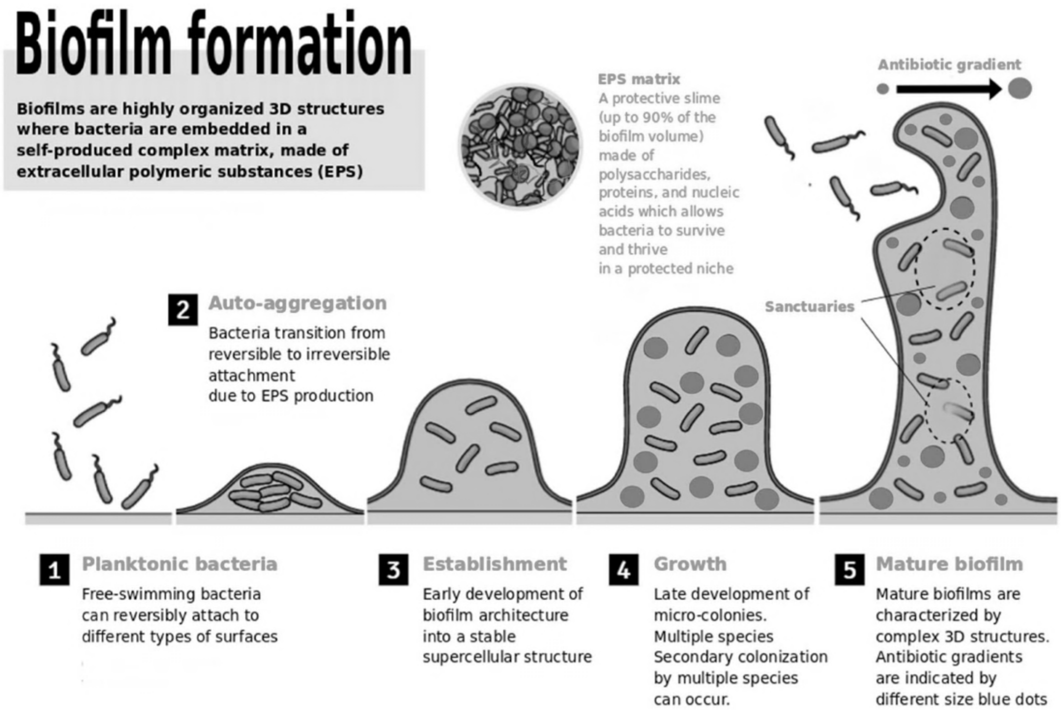


Figure II.2: Biofilm formation mechanism (de M Muliyadi et al., 2024).

II.3.2 Adsorption of pollutants

Once a stable biofilm has developed on the trickling filter media, it serves as the primary site for pollutant capture and transformation. As wastewater percolates over the biofilm-coated media, pollutants are retained by adsorption onto the EPS matrix and absorbed into the filter pores. The high surface area and porosity of the media increase contact efficiency, facilitating physical retention and promoting biochemical reactions within the biofilm (Dubey & Kashyap, 2022).

II.3.3 Oxygen and substrate transport mechanisms

Effective removal of contaminants in trickling filters depends on the transport of substrates (such as organic compounds and ammonia) and oxygen into and throughout the biofilm. This process occurs in two main phases: external transport from the wastewater to the biofilm surface and internal diffusion through the EPS matrix to reach the microbial cells.

II.3.3.1 External transport

External transport is governed by the flow of wastewater over the filter media. Substrates and dissolved oxygen are delivered to the biofilm surface via convective mass transfer, with the rate of delivery influenced by hydraulic loading rates and turbulence, which determine the thickness of the boundary layer surrounding the biofilm (Logan, 1994).

II.3.3.2 Internal diffusion and oxygen gradients

Once at the biofilm surface, oxygen and substrates must diffuse through the EPS matrix to reach the embedded microbial communities. This diffusion is slower than convective transport and represents the rate-limiting step for microbial metabolism (Wik, 2004). Oxygen typically penetrates only the outermost 0.1–0.3 mm of the biofilm, resulting in a vertical gradient (see Figure II.3):

- **Aerobic zone:** The surface layer, rich in oxygen, supports aerobic bacteria responsible for the oxidation of organic matter and nitrification.
- **Anoxic or anaerobic zone:** Deeper regions lack oxygen, enabling denitrification and fermentation by facultative and obligate anaerobes (EPA, 2000).

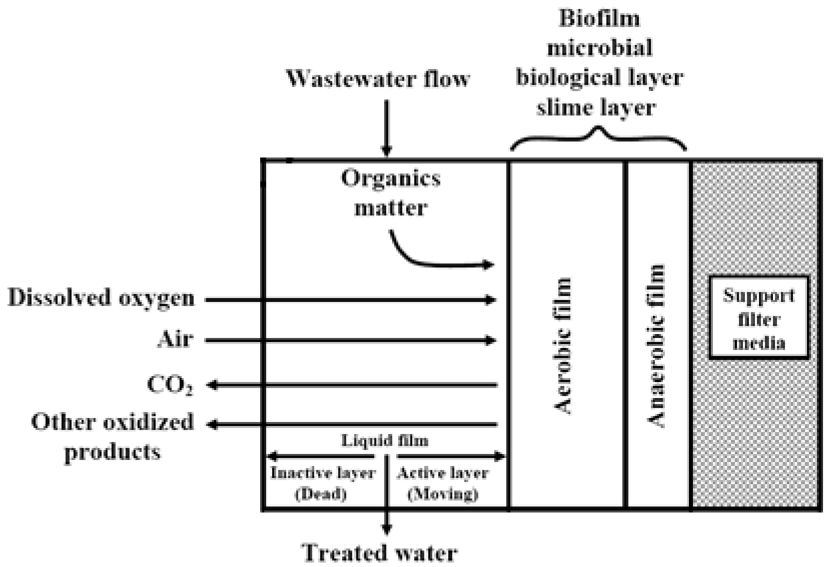


Figure II.3: Schematic diagram of purification mechanism in trickling filters (M. K. Jasim & A. M. Weli, 2011).

This stratification allows for simultaneous aerobic and anaerobic treatment within a single biofilm, thereby enhancing overall treatment efficiency (Flemming et al., 2016).

II.3.4 Matter conversion mechanisms

The efficiency of matter conversion in trickling filters depends on the metabolic diversity of the microbial community, the stratification of aerobic and anaerobic zones within the biofilm, and the dynamic interactions between physical, chemical, and biological factors.

II.3.4.1 Biodegradation of organic matter

Pollutant conversion in the biofilm is carried out by metabolically active microbial communities. In the oxygen-rich outer layers, aerobic heterotrophic bacteria oxidize organic matter into carbon dioxide and water, significantly reducing the biochemical oxygen demand (BOD) of the wastewater (EPA, 2000). Heterotrophic bacteria within the biofilm metabolize adsorbed organics via aerobic respiration, leading to the transformation of carbon-based compounds (approximated as CH_2O) into carbon dioxide (CO_2), water, and new microbial biomass ($C_5H_7NO_2$) as follows:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + biomass$$

The outer biofilm layer remains aerobic due to oxygen supplied by natural convection or forced aeration, allowing for the rapid breakdown of readily biodegradable matter. Oxygen diffusion diminishes with biofilm depth, creating anoxic or anaerobic zones that harbor facultative or anaerobic bacteria (Hung et al., 2021). This stratified microenvironment ensures that aerobic species dominate the surface while deeper layers accommodate fermentative processes producing gases like CH_4, H_2S, and CO_2. Over time, excess biofilm detaches due to self-scouring when inner layers become inactive, ensuring system stability and preventing clogging (MELCC, 2021).

II.3.4.2 Nitrification of ammoniacal nitrogen

Simultaneously, autotrophic nitrifiers such as Nitrosomonas and Nitrobacter convert ammonium into nitrate in a two-step process known as nitrification (Nourmohammadi et al., 2013). In addition to BOD removal, well-aerated trickling filters facilitate the nitrification of ammonium (NH_4^+) into nitrate (NO_3^-) via two sequential aerobic oxidation reactions:

- $NH_4^+ + 1.5\,O_2 \rightarrow NO_2^- + 2\,H^+ + H_2O$ *(*by Nitrosomonas*),*
- $NO_2^- + 0.5\,O_2 \rightarrow NO_3^-$ *(*by Nitrobacter*).*

Combined, these reactions produce:

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O$$

Nitrifiers are autotrophic bacteria that derive energy from these oxidations and use inorganic carbon (CO_2) for growth. However, their growth rate is slower than that of heterotrophs and is sensitive to environmental factors such as temperature (optimal 20–35 °C), pH (~7–8), and dissolved oxygen levels (>2 mg/L) (Baroud et al., 2018). Low organic loading is essential to prevent competition for oxygen. Recirculating nitrified effluent to the filter inlet reduces BOD concentrations and improves oxygen transfer and nitrification efficiency (Dorias & Baumann, 1994).

II.3.4.3 Denitrification of nitrates

The inner layers of the biofilm, which are often oxygen-depleted, support anoxic processes. Here, facultative anaerobic bacteria carry out denitrification, using nitrate as an electron acceptor to produce nitrogen gas, which is released into the atmosphere (Eubios, 1996). Denitrification is the anaerobic reduction of nitrate (NO_3^-) to nitrogen gas (N_2) by facultative heterotrophic bacteria under oxygen-deficient conditions. These bacteria use nitrate as an alternative electron acceptor, oxidizing a carbon source (e.g., methanol) and producing N_2, CO_2, water, and hydroxide ions:

$$NO^{3-} + 1.08\,CH^3OH + 0.24\,H^2CO^3 \rightarrow 0.47\,N^2 + 0.76\,CO^2 + 1.58\,H^2O + OH^-$$

In standard trickling filters, the predominantly aerobic conditions hinder spontaneous denitrification. However, selective oxygen control (e.g., covering the reactor or using a downstream anoxic zone) allows for targeted nitrate reduction (Dorias & Baumann, 1994). Experiments show that covered filters can achieve double the nitrogen removal efficiency compared to uncovered systems. Nevertheless, external denitrification reactors are commonly used in advanced treatment trains to supplement this function (MELCC, 2021). This dual-layered metabolic activity allows trickling filters to remove both carbonaceous and nitrogenous pollutants efficiently within the same treatment unit.

II.3.5 By-Product diffusion

In trickling filters, metabolically active biofilms continuously produce by-products such as carbon dioxide (CO_2), nitrate (NO_3^-), and nitrogen gas (N_2) as a result of organic matter degradation, nitrification, and denitrification. These compounds must diffuse out of the biofilm and return to the bulk wastewater, driven by concentration gradients. This diffusion is crucial to avoid the accumulation of inhibitory substances within the biofilm, which could compromise microbial metabolism and treatment efficiency (Web.DEU, 2024).

II.4 Factors influencing the treatment efficiency of trickling filters

The treatment efficiency of trickling filters is strongly governed by design parameters and operational conditions, including the nature of the support media, hydraulic and organic loading rates, and environmental factors. When properly optimized, these systems can achieve 80–90% biochemical oxygen demand (BOD_5) removal, but this efficiency may drop to 65–75% under excessive loading conditions (U.S. Environmental Protection Agency [EPA], 1998).

II.4.1 Nature of the support media

The support media used in trickling filters serve as the foundation for biofilm development and significantly affect both biological and operational performance. The surface roughness and porosity of the media directly influence microbial adhesion and biofilm stability. Surfaces with moderate roughness and high porosity provide more surface area and microscale protection from shear stress, fostering resilient microbial communities (Saini et al., 2023).

Cheng et al. (2023) showed that high-porosity nonwoven fabrics outperformed smooth materials in retaining biomass and enhancing pollutant removal, largely due to improved oxygen diffusion and microbial colonization. Conversely, Yang et al. (2023) demonstrated that superhydrophobic and ultra-smooth surfaces hinder microbial attachment under turbulent conditions. These findings emphasize the importance of selecting media that balance surface roughness and hydrophobicity to maximize microbial retention without increasing detachment risks.

Effective media should also be chemically inert, durable, and resistant to clogging. Traditional options such as pumice, coke, and crushed gravel offer specific surface areas of 45–60 m^2/m^3. In contrast, modern structured plastic modules can provide 90–150 m^2/m^3, enhancing aeration and preventing clogging due to their larger void volumes (Emergency-WASH, n.d.; EPA, 1998). Their lightweight design also supports vertical configurations, improving structural efficiency (Farmer, 2013). While ceramic-based materials are promising due to their porosity and durability, their use remains limited because of cost and availability constraints.

To prevent clogging and maintain performance, pretreatment steps such as sedimentation and screening are essential. Excessively thick biofilms may lead to anaerobic zones and detachment, compromising treatment outcomes.

II.4.2 Environmental parameters: temperature, pH, and oxygenation

Environmental factors, including temperature, pH, and oxygenation have a profound effect on microbial activity and biofilm structure in trickling filters.

Temperature impacts enzyme activity and microbial growth rates. In accordance with Van't Hoff's law ($Q_{10} \approx 2$), reaction rates double for every 10°C increase within the suitable range (EPA, 1998). Optimal nitrification occurs between 20–30°C, with a sharp decline in performance below 15°C. Saini et al. (2023) and Abu Hasan et al. (2024) reported that mesophilic microorganisms thrive best between 30–40°C, and temperature deviations impair EPS production and enzyme function.

pH also critically influences nitrification, with the optimal range being 7.0 to 8.0. Values below 6.5 hinder ammonium oxidation and microbial viability (EPA, 1993). Extreme pH levels (≤3 or ≥12) damage membranes and inhibit enzyme systems, compromising biofilm integrity (Saini et al., 2023). However, EPS can form buffering gradients that shield inner biofilm layers from such stress (Abu Hasan et al., 2024).

Oxygen availability is vital for aerobic respiration. Dissolved oxygen (DO) levels should exceed 2 mg/l to maintain efficient biofilm function, as levels below 1 mg/l severely limit nitrification (EPA, 1993). While passive aeration may suffice with porous media, forced aeration ensures uniform oxygen distribution and prevents anaerobic zones in deeper biofilm strata.

Other variables such as C/N ratios, toxic compounds, and hydraulic shocks can also impair biofilm health. High C/N ratios favor heterotrophs, reducing nitrification. Toxins like heavy metals and surfactants reduce microbial viability. Sudden hydraulic changes may induce excessive EPS production or sloughing (Abu Hasan et al., 2024). Maintaining stable environmental conditions is thus critical for reliable system performance.

II.4.3 Hydraulic and organic loading rates

Hydraulic and organic loads are central to determining biofilm activity and effluent quality. At low loading rates, biofilm growth is gradual but highly effective in removing pollutants due to limited endogenous respiration and efficient oxygen diffusion. In contrast, high organic loading leads to thicker biofilms, oxygen depletion, and anaerobic zones, reducing treatment efficiency (SUEZ, n.d.).

Low-rate trickling filters can achieve 85–90% BOD_5 removal, while high-rate filters, used as roughing filters, typically manage only 65–75%, necessitating additional treatment (EPA, 1998). Hydraulic loading affects system dynamics: low flows may encourage pests like filter flies, whereas excessive flows reduce contact time and may detach the biofilm (FONDAE, n.d.). SUEZ (n.d.) recommends hydraulic rates of 1.8 to 3 $m^3 \cdot m^{-2} \cdot h^{-1}$ for stable performance.

Recirculation of effluent helps buffer load fluctuations, dilute influent BOD, and improve oxygen availability, thus supporting nitrification and reducing clogging risks (EPA, 1998).

II.4.4 Hydrodynamics and shear stress

Beyond load parameters, hydrodynamics, especially shear stress, greatly influence biofilm structure. Increased flow velocities reduce the laminar boundary layer, enhancing substrate access but subjecting biofilms to mechanical stress. This can promote microbial adhesion initially but increases the risk of sloughing (Saini et al., 2023).

Moderate turbulence is beneficial, improving nutrient and oxygen transfer, particularly in deeper layers. Abu Hasan et al. (2024) found that such conditions stimulate EPS production, leading to stronger, more cohesive biofilms. However, excessive shear diverts microbial energy from pollutant degradation to structural maintenance, potentially decreasing treatment efficiency.

Maintaining a balance between turbulence and structural stability is essential for sustainable filter performance.

II.5 Practical applications and case studies of trickling filters

Trickling filters continue to demonstrate their versatility and operational reliability across various wastewater treatment contexts, effectively adapting to both conventional and advanced treatment needs when appropriately designed and maintained. Several real-world examples highlight the practical utility and optimization of trickling filters.

II.5.1 Operational robustness in semi-arid climates: the case of Khenifra, Morocco

In Khenifra, Morocco, a city of approximately 150,000 residents, a wastewater treatment facility employing pouzzolane-filled trickling filters has shown sustained success in semi-arid environmental conditions. This technology was selected for its operational simplicity, low energy requirements, and minimal oversight. Evaluations demonstrated significant reductions in organic loads and reliable adherence to effluent discharge standards (Baroud et al., 2018). A comparative analysis using Integrated Pollution Prevention and Control (IPPC) directive indicators showed the trickling filters outperforming aerated lagoons and activated sludge systems, achieving 42% more ratings in the “good to very good” category.

Key operational benefits observed included:

- High resilience to influent load fluctuations and toxic shocks
- Rapid biofilm regeneration after disturbances
- Minimal sludge production due to endogenous biomass stabilization within the biofilm

This case exemplifies the applicability of trickling filters in resource-constrained or rural settings, where ease of operation and resilience are paramount (Ministère de l’Environnement et de la Lutte contre les changements climatiques [MELCC], 2021).

II.5.2 Enhanced nitrification: the benfleet bio-tower upgrade, United Kingdom

To meet stricter ammonia discharge standards, several wastewater treatment facilities in the United Kingdom began upgrading conventional trickling filters with secondary bio-towers in the early 2000s. At the Benfleet plant in Essex, towers 6 meters high filled with high-surface-area plastic media were installed downstream of existing systems to facilitate tertiary nitrification (U.S. Environmental Protection Agency [EPA], 2000b).

Outcomes of the upgrade included:

- Reduction of ammonium concentrations from approximately 30 mg/L to below 5 mg/L
- Nitrification efficiencies above 80%
- Media surface area exceeding 100 m^2/m^3 to enhance microbial colonization
- Recycle flows minimizing biochemical oxygen demand (BOD) competition and enhancing aeration

This case demonstrates how optimized trickling filters with high-performance media and low-BOD influent can significantly contribute to advanced nitrogen removal processes (SUEZ, n.d.).

II.5.3 Optimizing denitrification: pilot studies in Germany

Historically, trickling filters were not considered suitable for denitrification due to their aerobic nature. However, pilot studies at the Stuttgart-Büsnau research facility in the early 1990s revealed that controlled anoxic conditions within enclosed trickling filters could significantly enhance denitrification performance. Researchers achieved this by feeding nitrified effluent to the filters, resulting in marked nitrate removal improvement (Dorias & Baumann, 1994).

Key findings included:

- More than 100% increase in nitrate removal compared to uncovered systems
- Implementation of a two-stage operational approach:
  - Stage 1: Aerobic nitrification
  - Stage 2: Anoxic denitrification facilitated by oxygen depletion and influent recirculation

Despite technical complexity and potential odor challenges due to sulfate-reducing bacteria, this method extends the capacity of trickling filters for comprehensive nitrogen removal (MELCC, 2021).

II.5.4 Additional applications: industrial and decentralized uses

Beyond municipal wastewater treatment, trickling filters have been successfully applied in several other contexts:

- Industrial Pretreatment: Used as roughing filters to reduce high-strength organic loads from industries like brewing and pulp production before secondary treatment.
- Decentralized Sanitation: Compact, containerized systems employed in small or remote communities, providing reliable treatment with low operational requirements.
- Hybrid Systems: Integrated with activated sludge systems, trickling filters serve as primary biological treatment units, supporting partial nitrification and protecting downstream biological units from overload (EPA, 2000a).

These cases emphasize the enduring value of trickling filters. Even with competition from newer technologies like moving bed biofilm reactors (MBBRs) and membrane bioreactors, trickling filters remain a robust, cost-effective, and energy-efficient option for diverse wastewater treatment scenarios.

Chapter III

Experimental study of the treatment performance of a trickling biofilter

III.1 Materials and experimental methods

III.1.1 Preparation and characterization of the synthetic effluent

For the purposes of this study, a synthetic effluent was prepared in the laboratory to simulate the key physicochemical characteristics of domestic wastewater. This methodological choice ensures homogeneous and reproducible experimental conditions while allowing precise control over the organic loads introduced into the biological reactor.

The effluent formulation was based on distilled water enriched with selected organic and mineral compounds. Glucose served as the primary source of readily biodegradable carbon, while urea supplied the nitrogen required for microbial metabolism. Mineral salts such as monopotassium phosphate (KH_2PO_4) and sodium chloride (NaCl) were added to replicate the ionic environment typically found in municipal wastewater. The pH of the solution was adjusted using diluted NaOH or HCl solutions to optimize conditions for biofilm development.

The composition of the synthetic effluent is detailed in Table III.1.

Table III.1: Composition of the synthetic effluent used in the experiments.

Composant	Concentration (mg/L)	Primary function
Glucose	300	Carbon source (COD)
Urée	30	Organic nitrogen source
KH_2PO_4	28	Phosphorus source
NaCl	100	Osmolarity maintenance
Distilled water	q.s.p. 1 litr	Solvent

The effluent was freshly prepared each day prior to experimentation to ensure its stability and quality. It was stored at room temperature (between 20 and 25 °C), and thoroughly homogenized before being introduced into the reactor to prevent sedimentation or alteration in composition.

A preliminary characterization of the effluent was performed to confirm its suitability for the intended experimental goals. The parameters analyzed included pH, chemical oxygen demand (COD), and five-day biochemical oxygen demand (BOD_5). Table III.2 summarizes the average values obtained.

Table III.2: Physicochemical characteristics of the synthetic effluent.

Parameter	**Mean value ± Standard deviation**
COD	500 ± 50 mg/L
BOD_5	250 ± 30 mg/L
pH	7.0 ± 0.2

The BOD_5/COD ratio of approximately 0.5 indicates a high level of biodegradability, typical of effluents suitable for biological treatment processes such as trickling filters.

The analytical techniques used for measuring these parameters, along with the data processing methods, are described in detail in Section III.3.

III.1.2 Description of the experimental setup

In this study, a pilot-scale aerobic trickling filter reactor was manually assembled in the laboratory to simulate, at a reduced scale, the biological treatment of domestic wastewater using a percolating biofilter system.

The reactor consists of a vertical cylindrical column made of transparent rigid PVC, allowing for downward gravitational flow of the synthetic effluent through a filter medium. This configuration ensures a large contact surface between the immobilized microbial community and the organic compounds to be degraded, thereby promoting aerobic biodegradation processes.

The setup was designed as a modular system to allow variation in experimental parameters (pH, temperature, hydraulic retention time, organic loading rate, support geometry, etc.) and to assess their influence on treatment efficiency (COD and BOD_5 removal, among others).

III.1.2.1 Components and materials used

The materials and components used in constructing the reactor were selected based on their availability, compatibility with biological treatment conditions, and ease of assembly in the laboratory. Figure III.1 illustrates all parts prior to assembly.

Main structural components of the reactor:

- A vertical column formed by rolling a rigid transparent PVC sheet (dimensions: 70 cm × 100 cm) to create the reactor body.
- Four metal threaded rods (Ø 1 cm, 100 cm long) with washers and nuts to secure the structure vertically in a stable, dismountable, and adjustable manner.

- Two circular rigid PVC flanges that anchor the threaded rods, providing the reactor's main support frame. These also support the base mesh and allow the installation of the rotating distribution system at the top.
- A metal mesh positioned at the column base to support the filter media while allowing air flow and treated effluent to pass through.

Bacterial support medium:

- The filter bed consists of natural gravel (grain size 15–75 mm), washed and dried, offering a large specific surface area for biofilm attachment.

Influent feeding and flow regulation system:

- A flexible transparent tube supplying the synthetic effluent.
- A PVC T-joint for fluid connection and directional control.
- A regulation valve for fine-tuning the influent flow rate.
- An upstream storage tank containing the synthetic effluent, and a downstream collector bucket to receive the treated effluent.

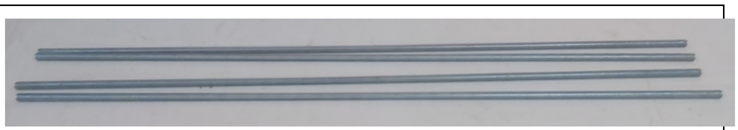
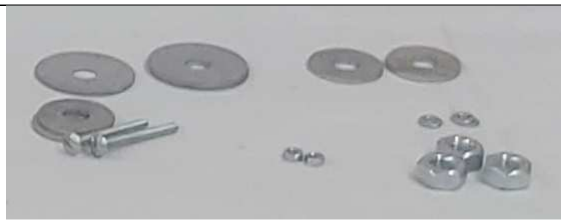
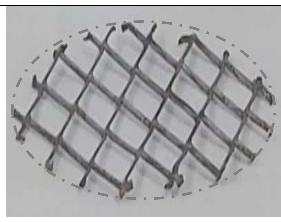
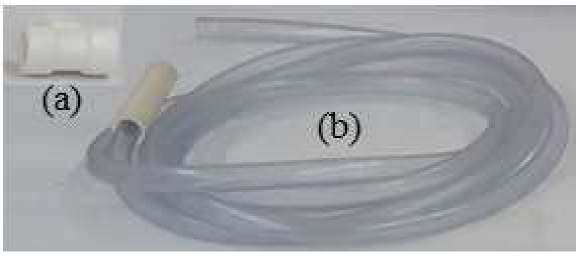
Effluent distribution system:

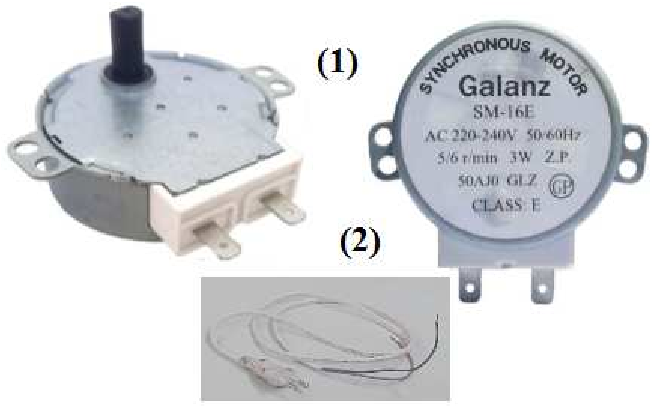
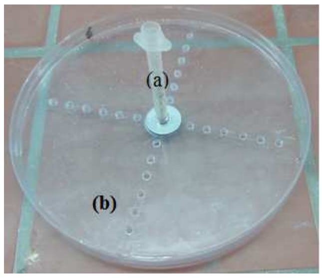
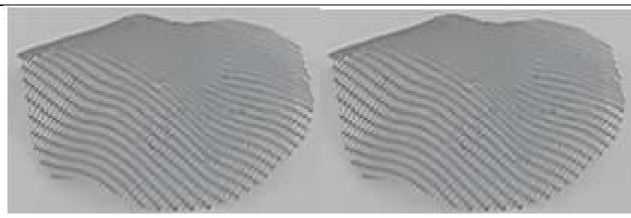
- A perforated circular plexiglass plate acting as a distributor, dispersing the effluent evenly across the filter bed.
- A small electric motor with an integrated rectifier, mounted at the reactor's top to drive the rotating distributor.
- An insulin syringe barrel functioning as a lightweight, stable rotation axis.
- A standard low-voltage power cord connected safely to a power source.
- An MDF support disc holding the motor securely in place, ensuring smooth and centered rotation.

Auxiliary components:

- Two pieces of mosquito net fixed to the upper section of the column for passive aeration while preventing insect intrusion.
- Standard laboratory tools (beakers, test tubes, sampling bottles) used for performance monitoring and sampling operations.

Main structure of the reactor	
Transparent rigid PVC sheet	

Metal threaded rods (Ø 1 cm, length 100 cm)	
Washers, bolts, and nuts	
Rigid PVC flanges	
Metal mesh grid	
Bacterial support medium	
Natural gravel	
Influent supply and regulation system	
((a) PVC T-joint connector (b) Flexible transparent tubing	
Flow control valve	

<table>
<tr><td>(A) Feed reservoir
(B) Effluent collection bucket</td><td>
</td></tr>
<tr><td colspan="2">Effluent Distribution System</td></tr>
<tr><td>(1) Electric motor
(2) Standard low-voltage power cord</td><td>
</td></tr>
<tr><td>(a) Rotation axis: insulin syringe barrel
(b) Distributor: perforated circular plexiglass cover</td><td>
</td></tr>
<tr><td>MDF support disc</td><td></td></tr>
<tr><td colspan="2">Auxiliary devices</td></tr>
<tr><td>Pieces of mosquito netting</td><td></td></tr>
</table>

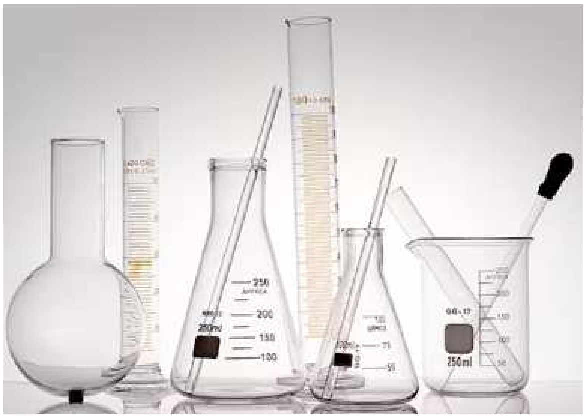
Standard laboratory equipment (beakers, test tubes, sampling bottles)	

Figure III.1: Components of the biofilter column

III.1.2.2 Biofilter column

The core unit of the system is a vertical transparent PVC column, 70 cm in height and 15 cm in internal diameter, with an estimated working volume of 12.4 liters. The transparent material allows for direct observation of effluent flow and biofilm development on the filter media, aiding experimental monitoring.

The column is held vertically by four Ø 1 cm metal threaded rods fastened between two rigid PVC flanges. The lower flange is raised 10 cm above the rod ends, creating a space for air circulation beneath the column. A metal mesh placed over the bottom flange supports the filter media (gravel, pozzolan, etc.) and serves two main functions:

- Enables even gravitational flow of effluent through the filter bed;
- Facilitates passive air entry from the base, maintaining optimal aerobic conditions inside the reactor.

This configuration enhances the "chimney effect," promoting natural convection by drawing ambient air from the bottom and releasing it from the top. This ensures passive ventilation without energy input, sustaining biological treatment performance.

III.1.2.3 Filter medium: Granulometric characterization of gravel

The filter medium used in this study consists of natural siliceous gravel sourced locally. Selected for its mechanical strength, chemical stability, and suitable particle size, this substrate offers a stable structure and high specific surface area conducive to microbial adhesion and biofilm development both critical for organic pollutant removal.

A detailed granulometric analysis was performed on a representative sample to determine the following physical properties:

- Water absorption coefficient
- Bulk density

- Equivalent spherical diameter
- Estimated specific surface area

These properties helped determine average particle size, mass-based size distribution, and total porosity of the filter bed. These parameters are crucial for understanding the substrate's hydraulic and biological behavior, as they influence water flow, oxygen transfer, biofilm stability, and overall treatment efficiency.

1. Water absorption coefficient

The water absorption coefficient reflects the gravel's capacity to absorb and retain moisture—an essential property for maintaining the bacterial biofilm, especially during temporary interruptions in influent supply.

It is calculated by comparing the dry mass of the material to its mass after 24 hours of immersion in water, using the following formula:

$$A = \frac{m_{wet} - m_{dry}}{m_{dry}} \times 100$$

Where:

A = Water absorption coefficient (%)

m_{dry} = Dry mass (g)

m_{wet} = Mass after 24 h immersion (g)

The results obtained as a function of particle size are presented in Table III.3.

Table III.3: Water absorption coefficient by particle size

Mean diameter	Absorption coefficient (%)	Remarks
< 4 mm	1.5 % – 2.5 %	High microporosity, good moisture retention
4 – 8 mm	0.8 % – 1.5 %	Balanced porosity/stability
> 8 mm	0.2 % – 0.8 %	Good drainage, lower retention

A higher absorption coefficient promotes moisture retention, thereby supporting microbial survival and ensuring continued biological activity within the reactor, even under variable hydraulic conditions.

2. Bulk density

Bulk density was determined by measuring the dry mass of gravel and the volume of displaced water after immersion in a graduated cylinder (Figure III.2), using the formula:

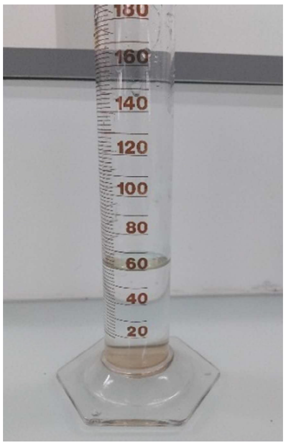
$$\rho_s = \frac{m}{V}$$

Where:

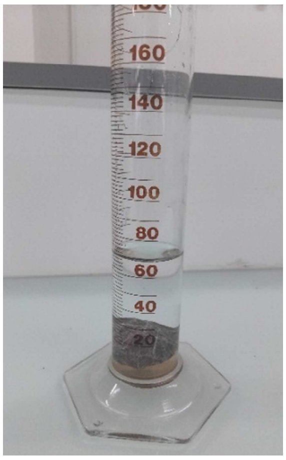
ρ_s = Bulk density (g/cm³)

m = Dry mass (g)

V = Displaced water volume (cm³)



Water level before immersion



Water level after immersion

Figure III.2: Experimental setup for measuring bulk density by water displacement method.

3. Equivalent mean diameter

The equivalent spherical diameter was calculated by approximating each gravel particle as a sphere of equal volume. This simplification facilitates the estimation of physical properties such as specific surface area and porosity. The following relationship was used:

$$d = \left(\frac{6m}{\pi \rho_s}\right)^{1/3}$$

Where:

d = Equivalent spherical diameter (cm)

m = Mass of the particle (g)

ρ_s = True density of the material (g/cm³)

Applying this formula to a representative sample yielded a characteristic average particle size for the gravel used in the study.

4. Granulometric organization of the filter media

To enhance the performance of the biofilter, the filter medium was stratified into three functional granulometric classes, each offering distinct physical and hydraulic characteristics (Table III.4).

Table III.4: Granulometric classes used in the biofilter packing

Class	Particle size range	Position in column	Primary function	Proportion of total volume
1	0–4 cm	Upper section (Fig. III.3a)	High specific surface area: initiates bacterial adhesion and rapid colonization	≈ 5–10 %
2	4–6 cm	Central section (Fig. III.3b)	Balance between porosity and stability: biological core of degradation processes	≈ 70 %
3	> 6 cm	Bottom section (Fig. III.3c)	Mechanical support and efficient drainage of treated effluent	≈ 20–25 %

The three granulometric classes of gravel were thoroughly washed with non-chlorinated water to remove dust and fine particles that could interfere with biofilm development. After air drying, the materials were freely poured into the reactor column. While no mechanical compaction was applied, the vertical arrangement respected a controlled granulometric stratification.

(A) (B) (C)

Figure III.3: The gravel medium

(A) 0–4 cm; (B) 4–6 cm; and (C) > 6 cm (support layer)

Each layer occupies approximately 20 cm in height, corresponding to markers at 20, 40, and 60 cm along the column wall (see Figure III.4), representing roughly 80% of the reactor's usable height. An upper free space of 10 cm was left to ensure uniform distribution of the synthetic effluent.

This configuration establishes an effective synergy among biological (bacterial adhesion), hydraulic (uniform percolation), and mechanical (support stability) functions, while remaining consistent with the experimental design protocol.

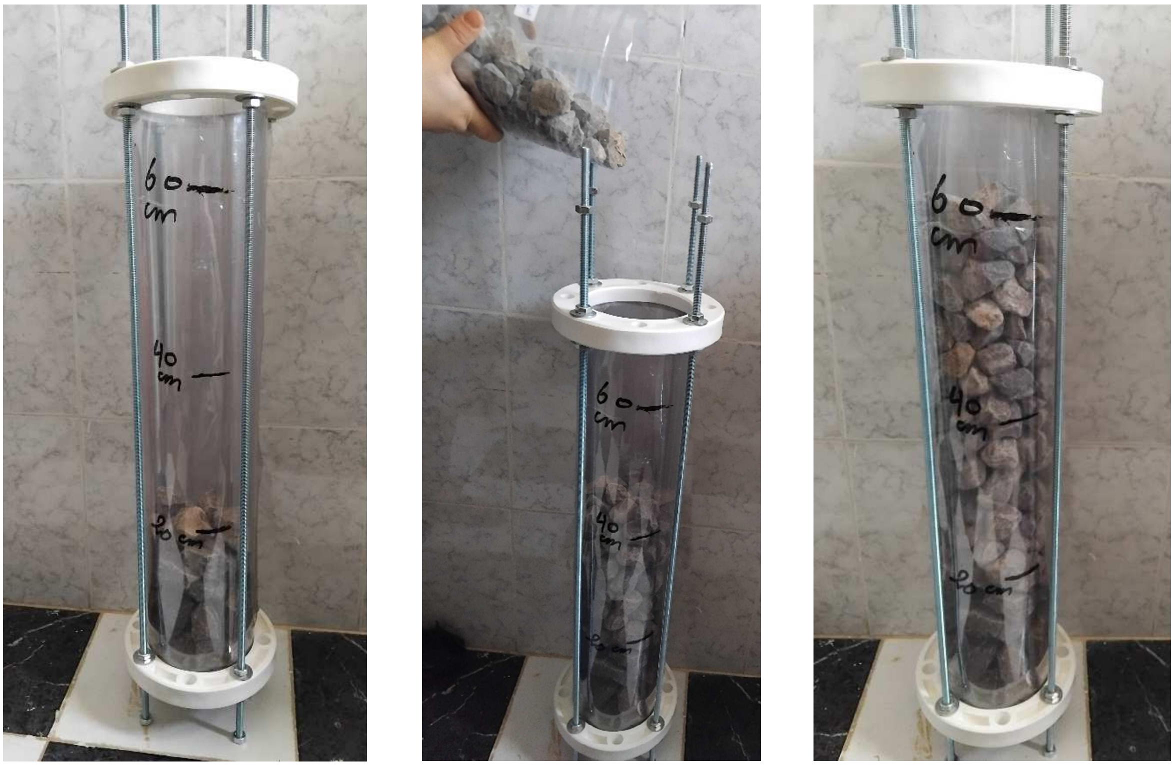


Figure III.4: Stratified filling of the biofilter reactor with graded filter material.

Markers at 20 cm, 40 cm, and 60 cm indicate the approximate distribution of the three granulometric layers introduced into the column.

5. Porosity (ε) or void ratio

Porosity, also referred to as void ratio, represents the proportion of the total volume occupied by the voids between the grains of the filter medium. This parameter is critical for both hydraulic and biological performance in biofilm-based systems, as it facilitates effluent percolation, enhances oxygen diffusion to the biofilm, and reduces the likelihood of clogging. A porosity value above 40% is generally considered optimal for maintaining an aerobic environment conducive to microbial activity.

In this study, porosity was experimentally determined using the water displacement method. The base of the reactor column was sealed, and distilled water was gradually added until the entire filter bed (height H = 60 cm) was saturated. The procedure was carried out carefully to avoid the formation of air bubbles, which could skew the results.

Porosity (ε) was calculated using the following equation:

$$\varepsilon = \frac{V_v}{V_t} \times 100$$

Where:

ε = Porosity, expressed as a percentage

V_v = Void volume (cm³), equivalent to the volume of water added

V_t = Total volume of the filter bed (cm³)

Given a total volume of 10.6 L (i.e., 10,600 cm³) and an introduced water volume of 4.8 L (i.e., 4,800 cm³), the porosity was found to be approximately 45%, which confirms the suitability of the filter bed for optimal performance in aerobic biofiltration systems.

6. Specific surface area (SSA)

Specific surface area (SSA) refers to the total surface area available for microbial attachment per unit volume of the filter medium. This parameter is pivotal to the biological efficiency of the trickling filter, as it directly influences biofilm development—central to organic matter degradation.

For granular materials approximated as spheres, SSA can be estimated using the following formula:

$$SSA = \frac{6 \times (1 - \varepsilon)}{d}$$

Where:

SSA = Specific surface area (expressed in cm²/cm³ or m²/m³)

ε = Porosity (expressed as a decimal, not a percentage)

d = Equivalent mean diameter of the grains (in cm)

This formula provides a practical estimate for designing biological filter media. In practice, an SSA between 60 and 80 m²/m³ is considered adequate for gravel-based beds, allowing effective bacterial colonization while maintaining proper effluent flow.

In this study, the calculated SSA was approximately 71.83 m²/m³, a value well within the recommended range. This result indicates sufficient microbial adhesion capacity and confirms the appropriateness of the selected filter material for achieving effective biological treatment.

II.1.2.4 Effluent distribution system

The effluent distribution system was designed to ensure an even dispersion of the synthetic effluent across the entire surface of the biofilm-supporting bed—an essential condition for the proper progression of biological treatment processes. The effluent is drawn from a feed reservoir using a flow-control valve and is conveyed to the top of the reactor via a flexible hose. Distribution is achieved through a rotary device consisting of a radially perforated circular plexiglass plate. This configuration enables uniform spreading of the liquid across the surface of the filter packing. The system is powered by a small low-voltage electric motor mounted on an MDF support disc, which provides both stability and centering. The rotation axis is made from an insulin syringe barrel, offering a lightweight structure and smooth rotational movement (see Figure III.5).

This mechanism allows for gradual and controlled sprinkling, minimizing the occurrence of oversaturated or dry zones and promoting homogeneous hydration of the biofilter bed. The effluent then percolates downward through the filter media by gravity and is collected at the bottom of the column through an outlet port.

The system operates in a discontinuous, single-pass mode without recirculation, simplifying the experimental setup while effectively reproducing real-world hydraulic conditions.

Figure III.5: View of the motorized rotary distribution system mounted at the top of the biofilter reactor.

III.2 Experimental methodology

The experimental protocol was designed to evaluate the evolution of key water quality parameters treated within an aerobic trickling filter reactor. The objective of the study is to compare the obtained results against regulatory thresholds while assessing the impact of variations in hydraulic and organic loading on the overall treatment performance.

III.2.1 Preparation of the biological support

Following the loading of the reactor with the filter media, a supplementary rinsing with tap water was performed to remove fine particles, particularly residual sand. This procedure aimed to ensure cleanliness, permeability, and uniformity of the packing—conditions that are essential for effective bacterial biofilm adhesion and development (Figure III.6).

Subsequent technical inspections were carried out to confirm the proper functioning of the experimental setup. These verifications included checking for any blockages, ensuring effective drainage, and confirming that the influent flow rates and hydraulic loads conformed to the values specified in the experimental protocol.

Figure III.6: Experimental setup.

III.2.2 Evaluation of hydraulic residence time (HRT)

To accurately assess the hydraulic behavior of the fixed-bed reactor, an experiment was conducted to determine the actual retention time of the effluent under varying hydraulic loading conditions. For this purpose, five measurement points were placed on the free surface of the filter bed, as shown in Figure III.7.

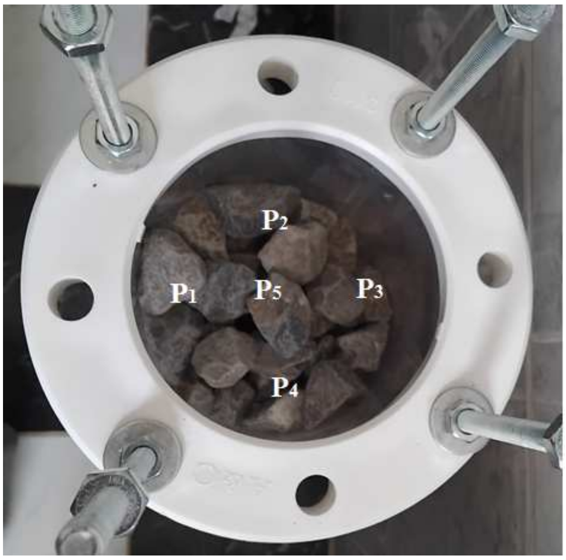


Figure III.7: Location of hydraulic residence time measurement points.

The adopted method was based on a single-pulse injection of a tracer at the reactor inlet, followed by time-resolved detection at the outlet.

The tracer used was a methylene blue solution with a concentration ranging from 0.1 to 0.5 g/L. A 50 mL pulse was injected instantaneously. This volume represented less than 0.4% of the reactor's total working volume (12.4 L), ensuring minimal disturbance to the internal hydrodynamics of the system.

The tests were carried out using volumetric flow rates (Qv) ranging from 0.18 L/min to 1.75 L/min. This range was selected to encompass both slow biological regimes and higher flow conditions simulating hydraulic overload.

For a cylindrical column with an internal diameter of 15 cm—equivalent to a cross-sectional area of 176.7 cm²—the corresponding daily hydraulic loading rates (HLR) were calculated using the following formula:

$$HLR = \frac{Q_v}{S} \times 10000$$

Where:

Qv = Volumetric flow rate (m³/day)

S = Surface area of the filter bed (m²)

This analysis made it possible to explore the impact of hydraulic regimes on reactor performance, including retention time, microbial colonization, and biodegradation efficiency.

Table III.5 summarizes the water flow times (in minutes) between each measurement point and the outlet, as recorded during the tests.

Table III.5: Variation of hydraulic residence time by flow rate and daily hydraulic load

Test	HLR (m³/m²·jour)	Qv (L/min)	Residence time (min)					Mean residence time (min)
			P1	**P2**	**P3**	**P4**	**P5**	
1	14,66	0,18	24,79	24,55	25,25	24,66	24,64	**24,78**
2	28,52	0,35	11,56	12,22	13,17	11,59	15,17	**12,74**
3	49,69	0,61	6,27	7,28	8,08	6,61	8,38	**7,32**
4	63,57	0,78	5,26	6,21	7,15	3,84	6,13	**5,72**
5	105,9	1,3	2,76	3,63	3,29	2,85	2,6	**3,43**
6	142,62	1,75	2,17	2,61	3,76	1,75	4,1	**2,55**

The results are illustrated in Figure III.8, which shows the evolution of residence times across the different measurement points, along with the average trend line.

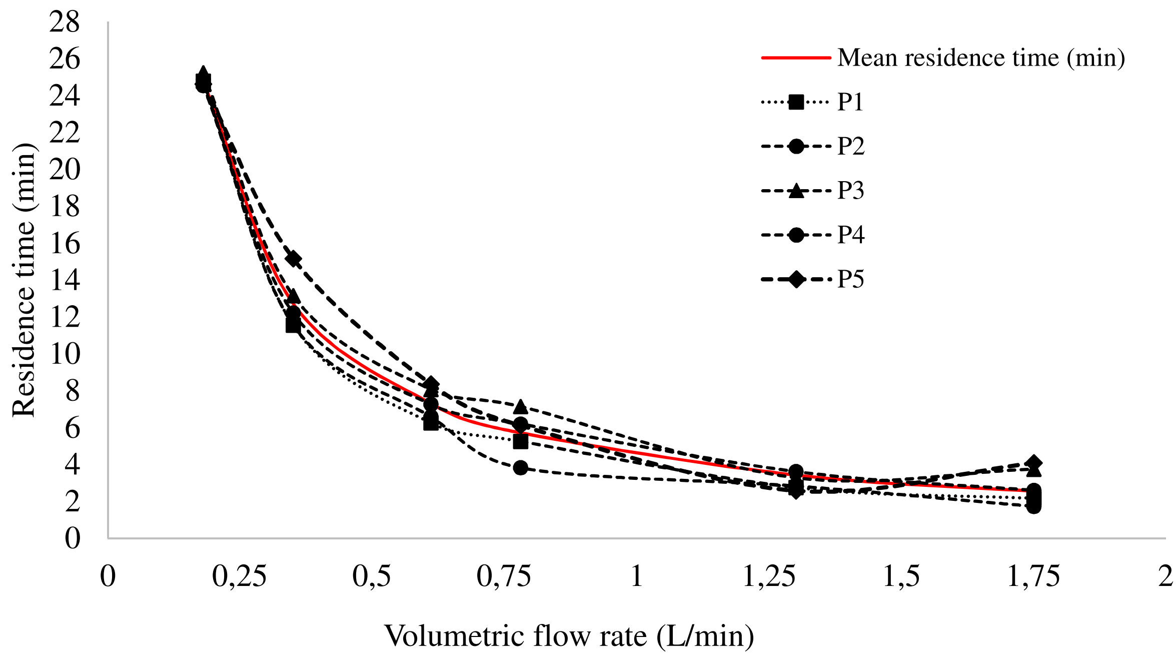


Figure III.8: Variation in hydraulic residence time as a function of influent flow rate.

The analysis highlights a clear inverse relationship between flow rate and retention time: as flow rate decreases, retention time increases. This behavior is typical of gravity-driven systems and reflects enhanced effluent retention at lower flow rates, which in turn favors microbial adhesion and improves the efficiency of biological processes.

At 0.18 L/min, the measured residence times approached 25 minutes, indicating prolonged contact between the wastewater and the filter medium. Conversely, as flow rates increased, the residence time declined potentially compromising the efficiency of slower biochemical reactions.

At intermediate flow regimes (0.6 to 1.3 L/min), variations between measurement points—especially between P3 and P5 suggest some flow heterogeneity, likely due to preferential pathways or channeling effects within the bed.

Finally, at the highest tested rate (1.75 L/min), residence times became both shorter and more homogeneous. While this uniformity suggests a more predictable flow profile, the reduced contact time may be insufficient to ensure optimal biological treatment.

The red curve in Figure III.7 represents the average trend and provides a comprehensive synthesis of the reactor's hydraulic behavior in relation to its filter configuration and operational conditions.

III.2.3 Microbial inoculation (Optional but recommended)

To accelerate the formation of an active biofilm on the filter media and to stabilize reactor performance more rapidly, microbial inoculation was implemented. Although this step is optional, it is strongly recommended under experimental conditions where minimizing the microbial community's adaptation time is critical.

The inoculum was obtained from fresh activated sludge collected from the secondary clarifier of a local wastewater treatment plant. This sludge, rich in both heterotrophic and autotrophic microorganisms, was applied directly to the surface of the filter bed using the direct pour method. A volume of 50 to 100 mL per liter of filter medium was used an amount considered optimal for column-type laboratory-scale reactors.

The inoculation process was carried out under strictly controlled environmental conditions to ensure effective bacterial adhesion and preserve cell viability. The operational parameters maintained during this phase were as follows:

- Stable ambient temperature: 20–30 °C
- Natural aeration: no forced air supply
- Low organic substrate concentration: diluted synthetic effluent or pretreated wastewater
- Consistent hydraulic flow: without abrupt fluctuations

After inoculation, the reactor was left undisturbed for 12 to 24 hours without circulation to allow initial microbial adhesion to the support medium. Constant moisture was maintained by periodic spraying with non-chlorinated water, and the reactor column was covered with a perforated plastic film to reduce evaporation while maintaining oxygen diffusion.

III.2.4 Start-Up procedure

The reactor was gradually brought into operation through a controlled increase in hydraulic flow, designed to support and structure biofilm formation. Initially, a moderate flow rate ranging from 0.05 to 0.1 L/min was applied for four consecutive hours, marking the onset of semi-continuous operation. Flow rate measurements were performed using a graduated cylinder and a stopwatch, and finely adjusted using a regulating valve.

Subsequently, a continuous flow ranging from 0.15 to 0.3 L/min was maintained for 24 hours, allowing stabilization of the hydraulic regime while avoiding hydrodynamic disturbances that could inhibit microbial adhesion. Over the following two to three days, the system operated at a flow rate between 0.35 and 0.6 L/min, without sampling, in order to preserve optimal conditions for microbial colonization and biofilm establishment.

Note: The first indicators of successful reactor start-up included:

- The appearance of a viscous film on the filter media, indicating initial biofilm formation
- A slight turbidity in the effluent, commonly observed during early start-up, reflecting bacterial mobilization (which gradually declines)
- A stable flow free of bubbles or leaks, confirming effective hydraulic control

From the fourth day onward, the system transitioned to continuous operation using synthetic wastewater at a flow rate of 0.35 to 0.6 L/min, maintaining a hydraulic retention time (HRT) between 15 and 30 minutes.

Biofilm development was monitored through regular visual inspections, based on criteria such as macroscopic appearance, uniformity of biological coverage, and early detection of potential clogging phenomena. Figure III.9 illustrates the progressive development stages of the bacterial biofilm on the siliceous gravel support, from the clean initial state to mature biofilm formation.

(1) Clean medium	(2) Initial adhesion (~24 h)	(3) Colonization (~7 days)	(4) Mature biofilm (~14 days)

Figure III.9: Bacterial biofilm development stages on siliceous gravel.

In parallel, effluent samples were collected every two days, both at the inlet and outlet of the reactor. Each sample underwent comprehensive analysis to monitor the evolution of treatment performance based on the following parameters: pH, temperature, five-day biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD).

All samples were stored at 4 °C immediately after collection and analyzed within 24 hours, in accordance with standard laboratory protocols to ensure data reliability.
Treatment efficiency was quantified by calculating the pollutant removal efficiency, using the following formula:

$$rendement = \frac{C_{entrée} - C_{sortie}}{C_{entrée}} \times 100$$

III.3 Analytical techniques and tools

III.3.1 pH measurement

pH is a fundamental indicator used to characterize the reaction medium and assess its influence on the biological activity of the biofilm. Measurements were taken before and after treatment using a digital pH meter (Hanna pH 210), equipped with a glass electrode filled with 4 M KCl solution (Figure III.10).
The device provides stable and continuous voltage readings, ensuring accurate pH measurements. Where necessary, the pH was adjusted using sulfuric acid (H_2SO_4 at 98%) or sodium hydroxide (NaOH) to maintain optimal conditions for microbial growth.

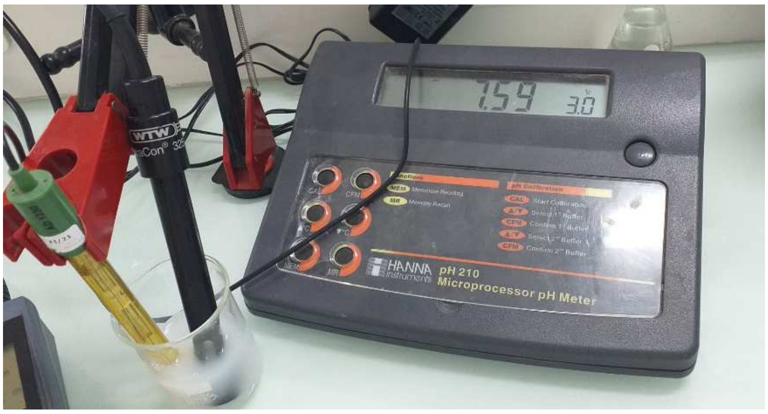


Figure III.10: Microprocessor pH Meter "Hanna pH 210".

III.3.2 Temperature measurement

Temperature is a key ecological factor in aquatic environments, influencing gas solubility, nutrient availability, and the kinetics of biological reactions. Elevated temperatures can lead to thermal pollution, disrupting aquatic ecosystems. Nitrification processes, in particular, are most efficient between 28 and 32 °C, but their effectiveness drops significantly between 12 and 15 °C and nearly halts below 5 °C (Rodier, Legube, & Merlet, 2005).

Effluent temperature was measured directly on the digital display of the pH meter at each sampling point to monitor the reactor's operating conditions.

III.3.3 Determination of chemical oxygen demand (COD)

Chemical Oxygen Demand (COD) estimates the amount of oxygen required to chemically oxidize the organic matter present in water. It is measured in the presence of excess potassium dichromate ($K_2Cr_2O_7$) in a highly acidic medium, catalyzed by silver sulfate (Ag_2SO_4) and stabilized with mercury sulfate ($HgSO_4$). The remaining dichromate is then titrated using ferrous ammonium sulfate.

Analytical procedure:

- Shake the tube to homogenize its contents.
- Add 2 mL of the sample to a COD reactive tube (LCK 114 or LCK 314) (Figure III.11a).
- Seal the tube with the threaded cap.
- Shake vigorously while holding the tube by the cap.
- Heat the tube for 120 minutes at 148 °C in a thermoreactor.
- Let it cool for 10 minutes, then bring to room temperature for at least 30 minutes.
- Measure the COD concentration in mg O_2/L using a DR2800 spectrophotometer (Figure III.11b).

(a) COD digestion reactor

(b) DR2800 spectrophotometer

Figure III.11: Equipment used for chemical oxygen demand (COD) measurement.

III.3.4 Determination of biochemical oxygen demand (BOD_5)

Biochemical Oxygen Demand over 5 days (BOD_5) quantifies the amount of oxygen required by aerobic microorganisms to break down biodegradable organic matter in water.

The method used is based on the automated OxiTop® system, which records the decrease in pressure inside a sealed bottle. This pressure drop results from oxygen consumption by microorganisms, offset by oxygen from the headspace in the bottle.

Figure III.12: OxiTop® system used for BOD_5 measurement.

Table III.6: Sample volume based on estimated BOD_5.

Volume (mL)	Expected BOD_5 range (mg/L)	Factor	Inhibitor drops
432	0 – 40	1	9
365	0 – 80	2	7
252	0 – 200	5	5
164	0 – 400	10	3
97	0 – 800	20	2
43.5	0 – 2000	50	1
22.5	0 – 4000	100	1

Experimental steps (Figure III.12):

- Collect the appropriate volume in a brown bottle.
- Add a magnetic stir bar.
- Introduce the nitrification inhibitor.
- Insert two NaOH pellets into the capsule.
- Screw the OxiTop® sensor onto the bottle.
- Press both S and M buttons simultaneously to start recording ("00" appears).

- Incubate the bottles at 20 °C for 5 days with inductive stirring.
- After incubation, record the final value.

$$DBO_5\left(\frac{mg}{L}\right) = \text{Displayed Value} \times Factor \text{ (From Table III. 6)}$$

III.4 Results and discussion

III.4.1 Evolution of physicochemical parameters

Monitoring the chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), and pH provided key insights into the performance of the fixed-bed reactor and the development dynamics of the biofilm throughout the treatment process.

Figure III.13 displays the concurrent evolution of COD and pH over time. During the first five days, COD levels decreased significantly, dropping from nearly 100 $mg \cdot L^{-1}$ to below 50 $mg \cdot L^{-1}$. This sharp decline indicates a rapid onset of effective biodegradation. Meanwhile, pH values remained stable between 8.0 and 8.2, suggesting a favorable environment for microbial activity.

Between days 6 and 9, a disturbance was observed: COD levels surged to approximately 180 $mg \cdot L^{-1}$, accompanied by a pH spike exceeding 8.5. This anomaly may be attributed to an organic overload, partial clogging, or structural imbalance in the biofilm—potentially exacerbated by excessive nitrification.

The following period (days 10–16) showed relative stabilization, with COD values ranging from 80 to 100 $mg \cdot L^{-1}$ and pH values between 8.0 and 8.4—conditions conducive to the activity of nitrifying bacteria. However, a late COD peak (~230 $mg \cdot L^{-1}$) appeared between days 17 and 20, signaling a disruption likely caused by a sudden organic surge or mechanical maintenance (e.g., reactor cleaning). The pH slightly declined toward 8.0, possibly indicating temporary weakening of the system's buffering capacity.

Figure III.14 illustrates the variation in BOD_5 throughout the treatment process. Initially, BOD_5 values increased markedly from approximately 70 to 170 $mg \cdot L^{-1}$ during days 0 to 4, likely reflecting the biofilm's adaptation to the incoming organic load. This phase was followed by a steep decline between days 4 and 7 (~20 $mg \cdot L^{-1}$), indicating a period of optimal microbial activity.

Another disturbance occurred on days 8–9, with a sudden BOD_5 spike (~200 $mg \cdot L^{-1}$), which may have resulted from partial biofilm detachment. From days 10 to 13, BOD_5 levels fluctuated between 30 and 140 $mg \cdot L^{-1}$, reflecting alternating phases of organic overload and system recovery.

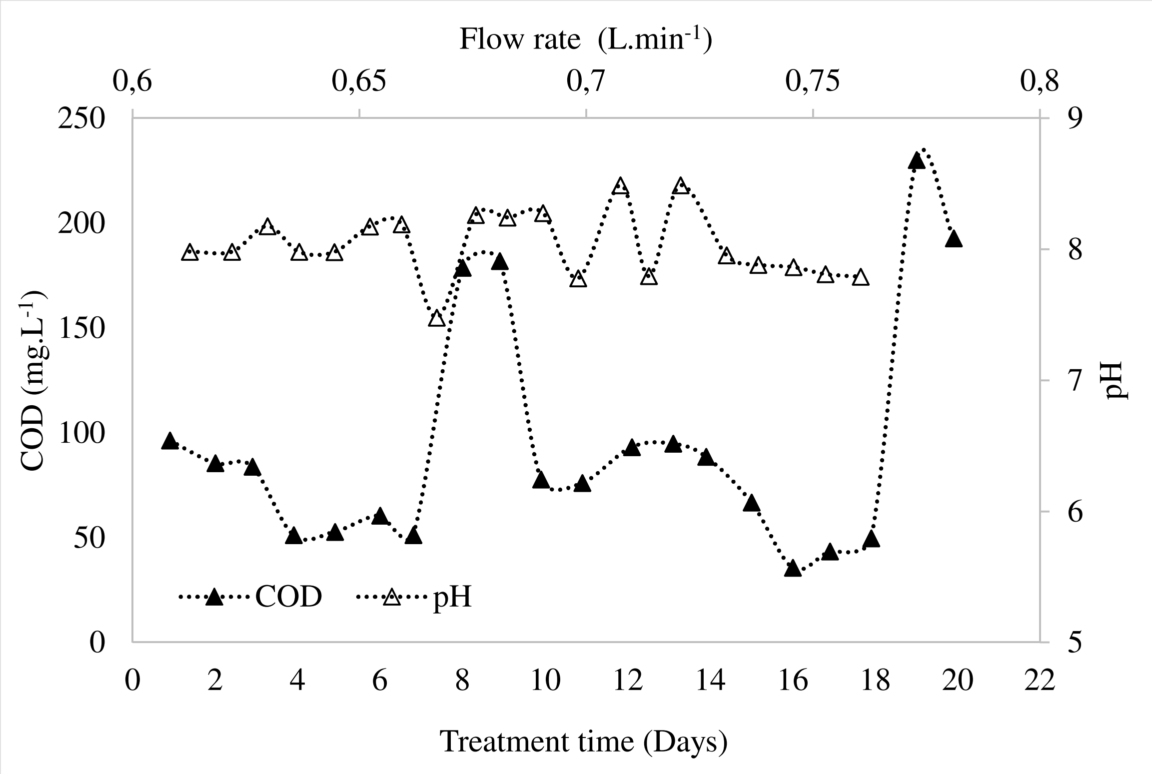


Figure III.13: Evolution of pH and COD in the effluent over treatment time (Influent COD = 621 ± 60.25 mg·L⁻¹).

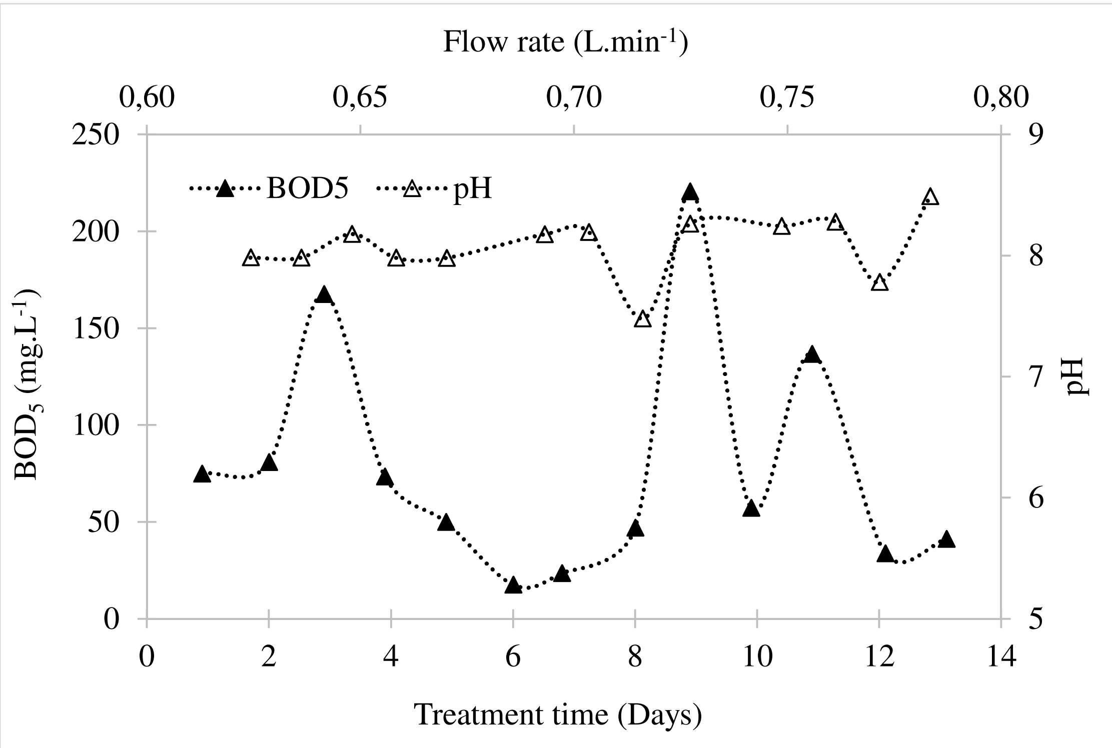


Figure III.14: Evolution of BOD_5 during biological treatment (Influent BOD_5 = 577 ± 52 mg·L⁻¹).

III.4.2 Treatment efficiency and mass removal Rates

The assessment of treatment performance highlights the influence of hydraulic loading rate on reactor efficiency.

III.4.2.1 Removal efficiency

Figure III.15 shows that COD removal efficiency peaked at a flow rate of 0.63 L/min (approximately 88–90%). This result suggests highly effective biodegradation under low flow conditions, due to longer contact time between the effluent and the biofilm. As the flow rate increased, efficiency gradually decreased, reaching 76–77% at 0.76 L/min. This drop can be attributed to reduced hydraulic retention time, which limits the extent of organic matter oxidation.

In contrast, BOD_5 removal exhibited greater resilience to increased flow rates. Efficiency remained consistently high across the tested range, with a maximum of 98–100% observed at 0.73 L/min, and only a slight decrease to 91–92% at 0.76 L/min. These findings underscore the biofilm's robustness in treating readily biodegradable compounds, such as those contributing to BOD_5, even under variable hydraulic conditions.

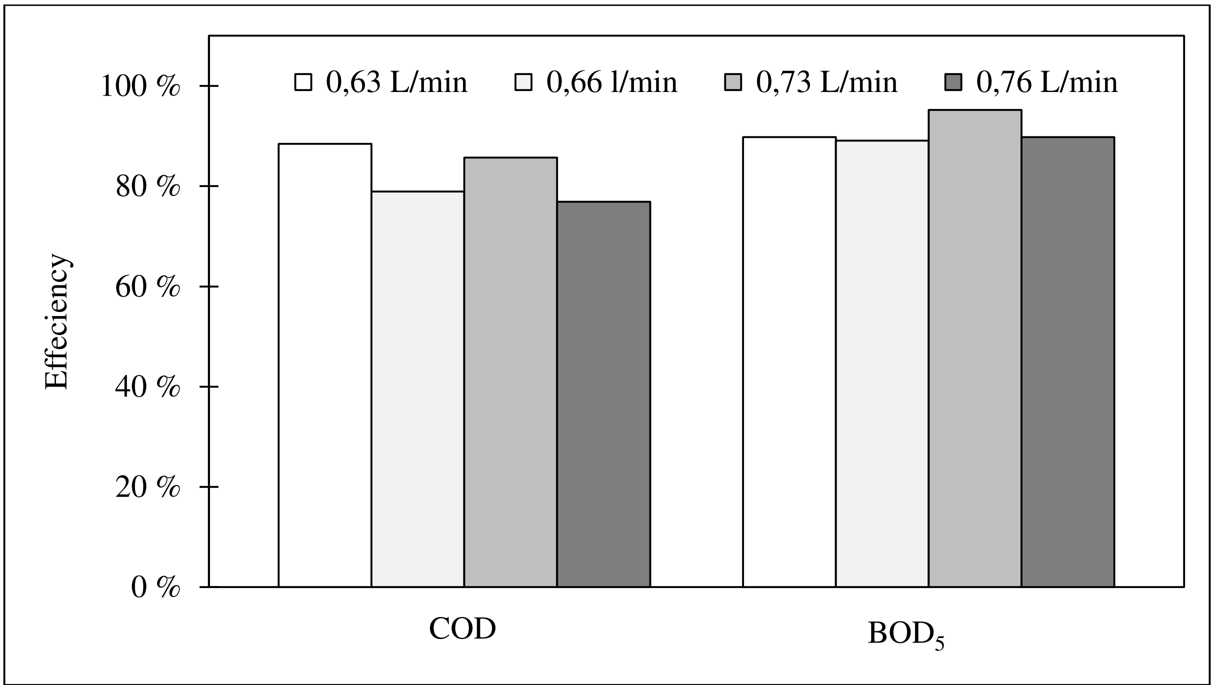


Figure III.15: Effect of influent flow rate on the removal efficiency (%) of COD and BOD_5

III.4.2.2 Mass removal rate

Figure III.16 complements this analysis by illustrating changes in mass removal rates (expressed in $g \cdot m^{-2} \cdot min^{-1}$). Unlike percentage-based efficiencies, these rates increased with flow rate. For COD, the removal rate rose from 0.30 to over 1.00 $g \cdot m^{-2} \cdot min^{-1}$ between 0.63

and 0.76 L/min. The maximum BOD_5 removal rate (~0.75 $g \cdot m^{-2} \cdot min^{-1}$) was recorded at 0.73 L/min, followed by stabilization.

These results indicate that higher flow rates allow the biofilm to handle greater organic loads, despite a slight decline in relative efficiency. This trade-off between removal percentage and mass treatment capacity highlights the operational flexibility of fixed-film systems. A flow rate of 0.73 L/min appears to offer the best compromise, ensuring both high BOD_5 removal efficiency and substantial mass treatment performance.

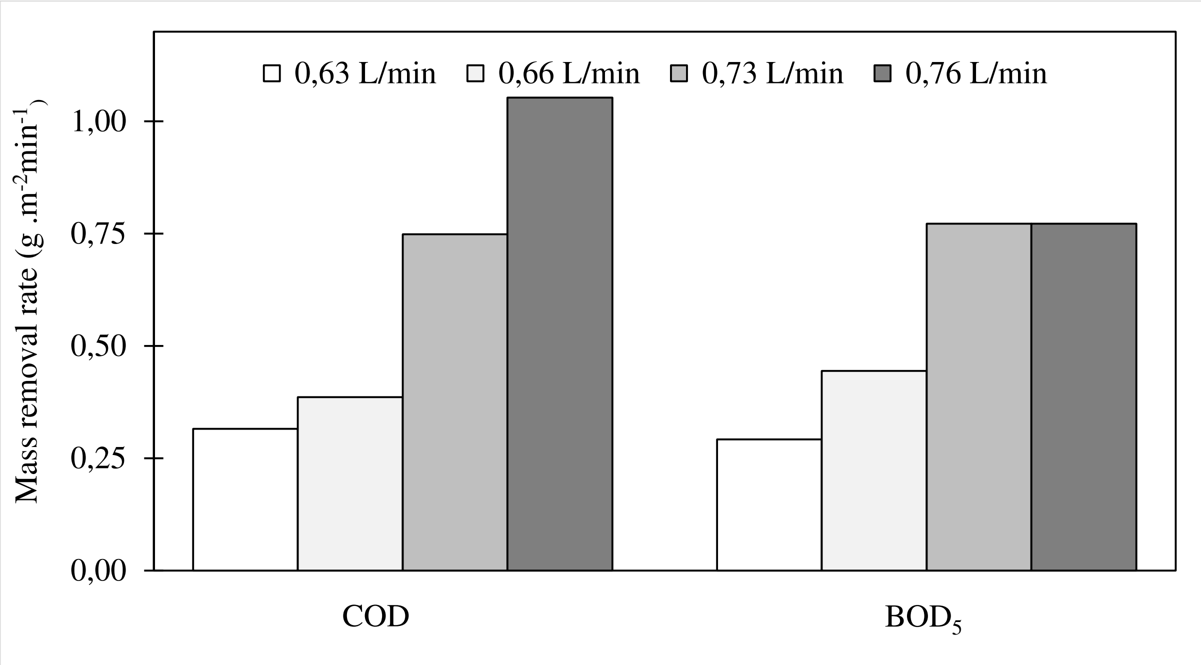


Figure III.16: Influence of influent flow rate on the mass removal rate of COD and BOD_5

General conclusion and perspectives

This study focused on evaluating the performance of a fixed-film biological reactor for the treatment of synthetic dairy effluent. The reactor was designed and operated under controlled laboratory conditions to investigate the effects of key parameters such as hydraulic loading rate, biofilm activity, and effluent quality dynamics on the overall treatment efficiency.

The analysis of physicochemical parameters—including Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), and pH—demonstrated that the reactor was capable of achieving significant pollutant removal under optimal operating conditions. The results showed that the COD and BOD_5 removal efficiencies were influenced by variations in influent flow rate. Notably, a flow rate of 0.73 L/min was identified as a compromise point, ensuring both high removal percentages and substantial mass elimination rates.

Throughout the experiment, the biofilm exhibited resilience and adaptability, capable of recovering from temporary disturbances such as organic overloading or hydraulic shocks. The results validate the potential of fixed-film systems in treating dairy wastewater with high organic loads, highlighting their robustness, ease of operation, and scalability for real-world applications.

Key Findings:

- COD removal efficiency peaked at 88–90% for moderate flow rates, with mass removal rates exceeding 1.00 $g \cdot m^{-2} \cdot min^{-1}$ at higher hydraulic loads.
- BOD_5 showed a more stable removal profile, maintaining high efficiencies (up to 100%) across a wider range of flow rates.
- The system demonstrated strong biofilm activity, with clear phases of adaptation, stabilization, and optimal pollutant degradation.
- pH remained within the favorable range (8.0–8.4), promoting nitrifying bacterial growth and enhancing treatment stability.

Perspectives for Future Work:

Given the promising results, several directions are recommended for further investigation:

- Pilot-scale implementation of the reactor to assess its behavior in real industrial conditions with actual dairy effluent.
- Modeling and simulation of the biofilm kinetics and hydraulic performance to optimize system design.

- Comparative studies with other biological and physicochemical treatment methods to validate cost-effectiveness and energy consumption.
- Exploration of biofilm-based hybrid systems, integrating additional treatment stages such as membrane filtration or anaerobic digestion, for improved resource recovery and sustainability.

In conclusion, this work serves as a solid foundation for the development of efficient, compact, and environmentally sustainable treatment technologies for the dairy industry.

الجمهورية الجزائرية الديمقراطية الشعبية

وزارة التعليم العالي و البحث العلمي

جامعة محمد بوضياف المسيلة

عنوان المشروع:

تقييم الأداء التطهيري للمرشح البكتيري

مشروع لنيل شهادة مؤسسة ناشئة في اطار القرار الوزاري 1275

الاسم التجاري

AquaBioTech

بطاقة معلومات:

(الخط: **Sakkal majalla**، حجم الخط14، تباعد أسطر1 سم)

حول فريق الاشراف وفريق العمل

1- فريق الاشراف:

فريق الاشراف	
المشرف الرئيسي : د. بكرنتشير خليدة	التخصص : هندسة الطرائق
المشرف المساعد : د. ميمون نبيلة	التخصص : تسويق وريادة الاعمال

2- فريق العمل:

فريق المشروع	التخصص	الكلية
الطالبة : حاجي آية	كيمياء البيئة	العلوم

1. **فكرة المشروع (الحل المقترح) :** مشروعنا يندرج ضمن مجال الخدمات البيئية، ويتمثل في تطوير واختبار كفاءة نظام معالجة بيولوجية للمياه المستعملة باستخدام مرشح بكتيري (trickling filter) . بدأت الفكرة نتيجة الحاجة الملحة الى حلول اقتصادية وفعالة لمعالجة المياه في المناطق ذات الموارد المحدودة .

سيتم اختبار أداء المرشح من خلال تحليل عدة مؤشرات تطهيرية (مثل BOD، COD، والمواد العالقة)، بهدف تحسين المعايير التشغيلية.

سيقوم فريق العمل بتنفيذ المشروع في مخبر كلية العلوم بجامعة المسيلة، بدعم من فريق اشراف متخصص في المعالجة البيولوجية.

2. **القيم المقترحة :**

يمكن أن تنشأ القيم المقترحة أو المقدمة للزبائن من خلال العناصر التالية :

- **الحداثة:** اول نظام مدمج منخفض التكلفة مصمم خصيصا للظروف الجزائرية .
- **الأداء:** ضمان إزالة عالية للملوثات العضوية بكفاءة تفوق المعايير الحالية .
- **التكييف:** إمكانية تعديل النظام حسب نوع المياه المراد معالجتها (منزلية، صناعية، فلاحية ...) .
- **إنجاز المهمة:** النظام يساعد المستخدم (بلديات، مزارعين، افراد) على معالجة المياه محليا دون الاعتماد على بنى تحتية مركزية او معقدة .
- **التصميم:** تصميم بسيط، مدمج، يمكن تركيبه بسهولة، وملائم للبيئات المختلفة (حتى المناطق الريفية) .
- **خفض التكاليف:** تكلفة التشغيل منخفضة (لا تحتاج طاقة كبيرة، . او صيانة معقدة) .
- **الحد من المخاطر:** تقليل المخاطر البيئية الناتجة عن تصريف المياه غير المعالجة
- **سهولة الوصول:** موجه خصيصا للبلديات الصغيرة، والمزارعين، والمناطق ذات البنية التحتية المحدودة – أي متاح حتى لمن لم يكن يقدر سابقا على المعالجة .
- **الملاءمة/سهولة الاستخدام:** تصميم بسيط وقابل للتشغيل بشكل آلي مع إمكانية التكامل مع أنظمة أخرى .

3. **فريق العمل :**

- الطالبة آية حاجي : طالبة ماستر 2 في كيمياء البيئة ، بمهارات في تحليل المياه، مكلفة بتصميم التجربة وتحليل العينات .

- تحت اشراف دكاترة مختصين في الكيمياء البيئية .

- توزيع المهام يشمل جمع وتحليل البيانات، تصميم النموذج التجريبي، وإعداد الوثائق التقنية .

- يعتمد الفريق على التنسيق المباشر داخل المخبر، والاجتماعات الدورية، بالإضافة الى استخدام البريد الالكتروني لتبادل المعطيات ومشاركة الملفات مع المشرفين او الشركاء، كما يتم التواصل مع المؤسسات والمهتمين عبر البريد الالكتروني والموقع الالكتروني للمشروع .

4. أهداف المشروع :

- تطوير نموذج اولي فعال من المرشح البكتيري .

- قياس كفاءة إزالة الملوثات العضوية .

- إمكانية تسويق النظام كمؤسسة ناشئة .

- الحصول على براءة اختراع محلية .

5. جدول زمني لتحقيق المشروع :

الشهر أو الأسبوع

الأعمال

			1	2	3	4	5	6	7
1		البحث في قواعد البيانات الخاصة ببراءات الاختراع وجمع المعلومات	✓	✓					
2		الشروع في الاختبارات المخبرية لإعداد النموذج الأولي		✓	✓				
3		تجريب النموذج الأولي		✓	✓	✓			
...		تجربة النموذج الأولي خارج المخابر			✓	✓	✓		
ن		تسجيل براءة الاختراع من اجل الحصول على رقم الإيداع والحماية الصناعية						✓	
...		متابعة عملية الحصول على براءة الاختراع وتصحيح ملاحظات الممتحنين من **inapi**							✓

6. عرض القطاع السوقي :

-السوق المحتمل :

- المستثمرون في مشاريع الاستدامة البيئية

- الجمعيات البيئية والتنموية المحلية

- مراكز البحث العلمي

- السوق المستهدف (الشريحة) :

- البلديات والمؤسسات العمومية المكلفة بالصرف الصحي

- محطات معالجة المياه المستعملة الصغيرة والمتوسطة

- الشركات الصناعية المهتمة بالتطهير البيئي

- مبررات الاختيار : الحاجة لحلول معالجة مياه مستعملة منخفضة التكلفة وسهلة الصيانة

- امكانية التعاقد مع هذا السوق : نظرا للحاجة الملحة لحلول معالجة المياه البيئية، يمكن ابرام عقود مباشرة مع :

- مديريات البيئة والبلديات لتحسين محطات التطهير .

- مؤسسات صناعية تحتاج لحلول داخلية لمعالجة المياه المستعملة .

كما ان المشروع مدعوم من طرف الحاضنة الجامعية مما يعزز فرص الوصول الى الشراكات الرسمية .

7. قياس شدة المنافسة :

- المنافسون المباشرون : هم الشركات او المخترعون الذين يقدمون أنظمة معالجة مياه بيولوجية او طبيعية، مثل :

- شركات صغيرة تصنع مرشحات مائية طبيعية .

- مراكز بحث في الجامعات يقومون بصنع نماذج معالجة مياه بطرق بيولوجية .

- جمعيات بيئية لديها مشاريع تطهير مائي في المناطق الريفية .

- المنافسون غير المباشرين : هم :

- شركات تقدم أنظمة معالجة كيميائية تقليدية .

- البلديات التي تعتمد شبكات صرف بدون معالجة دقيقة .

- عددهم وحصصهم السوقية :

- توجد في الجزائر اكثر من **200** محطة تطهير (محلية او اجنبية المنشأ) ،تعتمد على التهوية او الحمأة المنشطة .

- الحصة السوقية للأنظمة الهوائية تقدر ب 70-80% من السوق الوطنية في مشاريع البلديات .

- الأنظمة البيئية البديلة (مثل المرشحات الطبيعية او البيوفيلتر) تمثل اقل من **10%** .

- نقاط القوة عند المنافسين :

- خبرة مسبقا .

- اعتماد بعض الأنظمة دوليا.

- توفر شبكات توزيع .

- نقاط الضعف :

- تكاليف انجاز وتشغيل مرتفعة (الطاقة، صيانة المضخات) .

- أداء ضعيف في إزالة بعض الملوثات العضوية .

- ضعف الانتشار في المناطق الريفية او النائية .

8. التكاليف والأعباء :

1- **اقتناء الأصول الثابتة : المادية والمعنوية**

التجهيز	العدد	تكلفة الوحدة	التكلفة الإجمالية
حوض تجريبي (lit bactérien pilote)	1	350,000دج	350,000دج
مضخة مياه	1	80,000دج	80,000دج
جهاز قياسDBO/DCO	1	250,000دج	250,000دج
جهاز قياس pH و O_2	1	60,000دج	60,000دج
كمبيوتر لتحليل البيانات	1	120,000دج	120,000دج
معدات مخبرية) أنابيب، كواشف،(...	1	90,000دج	90,000دج

دج 950,000 :المجموع

2- المشتريات من المواد الأولية (الأصول المتداولة)

أ. للوحدة الواحدة من منتوجي

المادة	العدد	تكلفة الوحدة	التكلفة الإجمالية
مياه مستعملة خام)نقل/جمع(	12شهر	10,000دج	120,000دج
كواشف كيميائية	12	4,000دج	48,000دج
محلول معايرة ومراقبة	6	3,000دج	18,000دج
قفازات وأقنعة ومعدات وقاية	12	1,500دج	18,000دج

دج 204,000 :المجموع

ب .مجموع الإنتاج السنوي

التكلفة الإجمالية	تكلفة الوحدة	العدد	المنتج
60,000دج	5,000دج	12	تقارير أداء المعالجة (DBO, DCO, MES...)
28,000دج	7,000دج	4	عروض توعوية/نتائج بحث

دج 88,000 :المجموع

3- **أجور عمال المؤسسة**

إجمالي الرواتب السنوية	إجمالي الرواتب الشهرية	الراتب الشهري	العدد	الوظيفة
0دج	0دج	0دج	1	باحث رئيسي()طالب
180,000دج	15,000دج	15,000دج	1	مشرف علمي رمزي()
240,000دج	20,000دج	20,000دج	1	مساعد تقني/مخبري

دج 420,000 :الإجمالي

التكاليف الأخرى المتفرقة (داخلية أو خارجية

المبلغ	التموين	التصنيف
30,000دج	شخصي	تنقل ميداني
15,000دج	شخصي	طباعة وقرطاسية
12,000دج	شخصي	اتصال) إنترنت + هاتف(

دج 57,000 :المجموع

ثانيًا :رقم الأعمال المتوقع

N-2	N-1	N	N+1	N+2	N+3	N+4
Quantité produit A	12	20	24	30	36	40
Prix HT produit A	5,000 دج	5,000 دج	5,000 دج	5,000 دج	5,000 دج	5,000 دج
Ventes produit A	60,000 دج	100,000 دج	120,000 دج	150,000 دج	180,000 دج	200,000 دج
CHIFFRE D'AFFAIRES GLOBAL	60,000 دج	100,000 دج	120,000 دج	150,000 دج	180,000 دج	200,000 دج

9. النموذج الاولي التجريبي

الملحق رقم 04:
نموذج العمل التجاري

<table>
<tr>
<td rowspan="2">الشراكات الرئيسية
Key Partners
- الشركاء الرئيسيون :
- حاضنة الاعمال لجامعة المسيلة
- دار المقاولاتية بجامعة المسيلة
- الجامعات ومخابر البحث
- الوكالة الوطنية للموارد المائية
- بنوك داعمة للمشاريع المستدامة
- الصندوق الوطني للمؤسسات الناشئة
- شركات التأمين
- البلديات والمؤسسات العمومية المكلفة بالصرف الصحي
- وسائل الاعلام والتسويق
- الجمعيات البيئية</td>
<td>الأنشطة الرئيسية
Key Activities
- التخطيط والدراسات الأولية :
- جمع وتحليل المعطيات حول مياه الصرف
- تصميم نموذج تشغيلي للمرشح البكتيري
- إجراء دراسات مقارنة
- الإنتاج : وذلك من خلال تركيب وتشغيل النظام التجريبي
- رصد الأداء بمرور الزمن
- إدارة الصيانة
- التسويق :
- الترويج للتقنية كحل مستدام منخفض التكلفة
- إعداد عروض فنية موجهة للبلديات والمصانع
- التواصل مع شركات الهندسة البيئية</td>
<td rowspan="2">القيم المقترحة
Value Proposition
نظام المعالجة البيولوجية بالمرشح البكتيري (lit bactérién expérimental) هو مشروع مؤسسة ناشئة متخصصة في حلول معالجة المياه ، يقدم القيم التالية :
- البساطة والفعالية : نظام معالجة بيولوجية بسيط وفعال، يعتمد على تمرير مياه الصرف عبر وسط مغطى بطبقة من البكتيريا التي تحلل الملوثات العضوية
- الحداثة والابتكار : تقديم حل بيئي مبتكر يعتمد على تقنية " السرير البكتيري " لمعالجة المياه المستعملة
- القيمة بالحد من المخاطر : تقليل المخاطر البيئية الناتجة عن تصريف المياه غير المعالجة
- القيمة بالتخصيص او التلاؤم : إمكانية تصميم النظام بأحجام مختلفة ليتناسب مع الحاجات المختلفة للمخابر ومحطات المعالجة
- القيمة بالخدمة الشاملة : توفير نظام متكامل يشمل التصميم ، التركيب ، التكوين والمتابعة التقنية
- القيمة بالاداء العالي: تحقيق كفاءة تنقية عالية من خلال</td>
<td>العلاقات مع العملاء
Customer Relationships
- خلق العلاقة مع الزبائن بواسطة : ورشات توعوية حول أهمية معالجة المياه المستعملة
- تطوير العلاقة من خلال : تطوير وتحسين النظام بالإضافة الى تخفيض الأسعار
- استدامة العلاقة بواسطة : متابعة أداء النظام بعد التركيب بالإضافة الى دعم فني وتدريب مستمر للمستفيدين</td>
<td rowspan="2">شرائح العملاء
Customer Segments
- السوق المستهدف :
والمتمثل في :
– البلديات والمؤسسات العمومية المكلفة بالصرف الصحي
- محطات معالجة المياه المستعملة الصغيرة والمتوسطة
- الشركات الصناعية المهتمة بالتطهير البيئي
- السوق المحتمل : وهم العملاء :
- المستثمرون في مشاريع الاستدامة البيئية
- الجمعيات البيئية والتنموية المحلية
- مراكز البحث العلمي</td>
</tr>
<tr>
<td>الموارد الرئيسية
Key Resources
- الموارد المادية : الحوض او الخزان الخاص بالفلتر
- منظومة توزيع المياه
- مضخات ومعدات التحكم في التدفق
- معدات التحليل المخبرية (أجهزة تحليل المؤشرات الفيزيائية والكيميائية)</td>
<td>القنوات
Channels
- القنوات المباشرة :
- تنظيم لقاءات مباشرة مع ممثلي البلديات، شركات الهندسة البيئية ، ومسؤولي محطات المعالجة</td>
</tr>
</table>

	- تنظيم ورشات عمل تقنية لفائدة المشغلين والمهندسين المختصين - تنفيذ مشاريع تطبيقية ميدانية بالتعاون مع شركاء محتملين لعرض فعالية النظام في الواقع **- القنوات غير المباشرة :** - نشر مقالات علمية في مجلات محكمة متخصصة في معالجة المياه - المشاركة في المؤتمرات والندوات الوطنية والدولية لعرض نتائج الدراسة - نشر محتوى رقمي (تقارير، فيديوهات تعريفية) عبر مواقع الانترنت والمنصات الاجتماعية	الاستفادة من النشاط البيولوجي للبكتيريا **- القيمة بالسعر:** نظام اقتصادي وفعال مقارنة بالانظمة الأخرى المكلفة وبالتالي سوف يقدم سعر تنافسي **- التقليل من التكاليف عن طريق :** - استخدام مواد محلية في بناء النظام - بساطة التشغيل والصيانة - عدم الحاجة الى طاقة كبيرة او تقنيات معقدة **- سهولة الاستخدام :** نظام سهل التشغيل والصيانة ولا يتطلب خبرة تقنية متقدمة	**- الموارد البشرية :** - فريق البحث (أساتذة مشرفون وخبراء في معالجة المياه ، طلبة باحثون ومهندسون متربصون في المشروع ، شركاء خارجيون : تعاون محتمل مع محطات معالجة المياه وشركات الهندسة البيئية) **- الموارد المالية :** - وكالة دعم المشاريع الصغيرة والمتوسطة - وكالة تمويل البحث العلمي **- الموارد التكنولوجية :** - تكنولوجيا المرشح البكتيري ، أدوات قياس **- الموارد الفكرية :** - المعرفة العلمية المتخصصة في تقنيات المعالجة البيولوجية لمياه الصرف - المراجع العلمية الحديثة - الخبرة الاكاديمية والبحثية (خبرة الأساتذة المشرفين على المشروع)	

<table>
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هيكل التكاليف
Cost Structure
- **التكاليف الاستثمارية :** منها بناء النظام ، التجهيزات ...
- **التكاليف التشغيلية :** ومنها مراقبة الأداء ، رواتب الفريق ، صيانة ومتابعة بعد التركيب وتكاليف الترويج والتدريب

</td><td colspan="3">

مصادر الإيرادات
Revenue Streams
- بيع نظام المعالجة البيولوجية
- خدمات التصميم والتركيب
- عقود الصيانة والتركيب والاصلاح
- تمويل المشاريع ودعم الأبحاث المستقبلية (أي منح مالية تقدمها هيئات وطنية او دولية لدعم تطبيق نتائج البحث في مشاريع معالجة المياه)
- رخص الامتياز

</td></tr>
</table>

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