AIRLIFT AND PACKEDBED BIOREACTORS FOR WASTEWATER TREATMENT

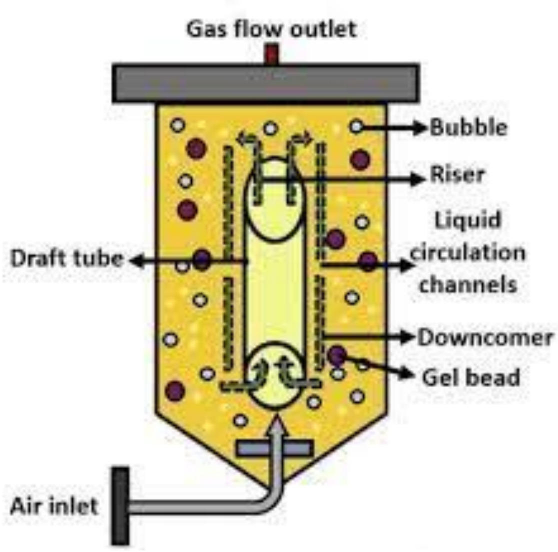
Edited by: Dr. Nikhil Mishra

AIRLIF BIOREACTORS

An airlift bioreactor (ALR) adapted for anaerobic wastewater treatment utilizes gas, typically the generated biogas, to mix and circulate the reactor's contents. This approach is energy-efficient and creates a low-shear environment suitable for anaerobic microbes. It is a tank that uses a recirculating liquid flow to mix its contents, but does not use air. Instead of compressed air, anaerobic systems use other gases, such as the biogas produced during digestion, to agitate the reactor contents. The simple design makes it an efficient and cost-effective system for treating high-strength wastewater.

Principles of operation

Like other ALRs, anaerobic ALRs circulate a "broth" (liquid and suspended solids) using gas to create a density difference.



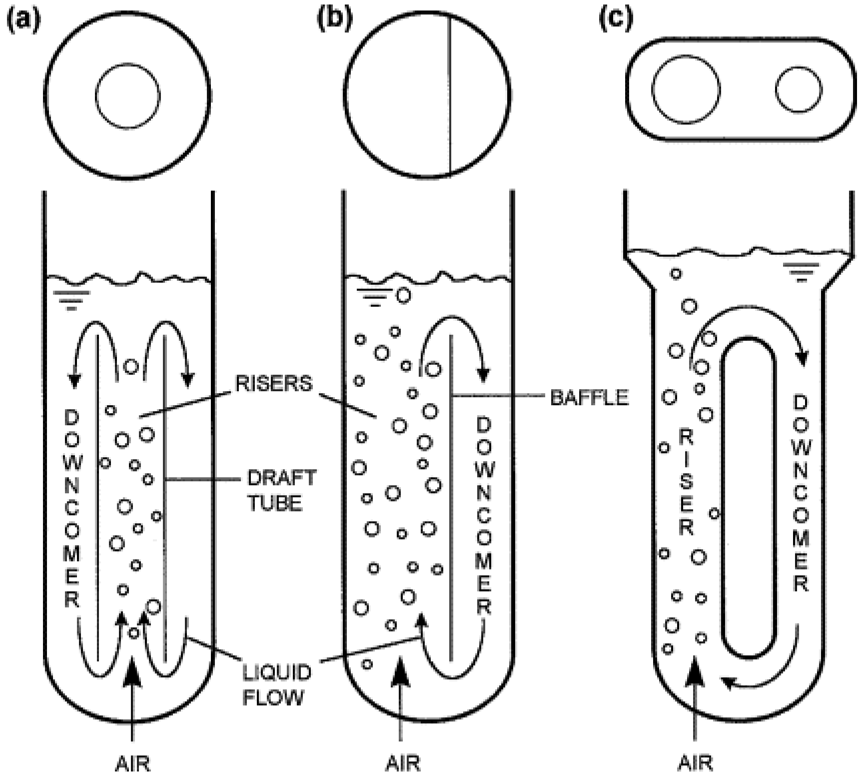


Fig: Airlift bioreactors: (a) draft-tube internal-loop configuration, (b) a split-cylinder device, and (c) an external-loop system.

- **Structure**: A partition—either a draft tube (internal-loop) or an external column (external-loop)—separates the reactor into a riser and a downcomer.
- **Gas injection**: Biogas is continuously or intermittently sparged into the bottom of a compartment known as the **riser**. For this purpose a gas sparger is used that injects biogas at the base of the riser.
- **Liquid circulation:** The gas bubbles reduce the density of the fluid in the riser, causing it to rise. The fluid then flows into the interconnected **downcomer** region, where there is little to no gas, and sinks.

- **Hydrodynamic Mixing**: This continuous gas-driven circulation provides the necessary mixing to ensure good contact between the wastewater, microbes, and nutrients. It eliminates the need for mechanical stirrers, which reduces energy costs and maintenance. The gas-liquid mixture in the riser has a lower density than the fluid in the downcomer, causing the fluid to circulate.
- **Anaerobic condition**: The absence of injected air maintains the oxygen-free conditions necessary for anaerobic microbes.
- **Biogas recirculation**: Recirculating the generated biogas enhances mixing and mass transfer without adding oxygen, which is lethal to the anaerobic microorganisms that drive the process.

Key design and operational parameters

The performance of an anaerobic airlift bioreactor is influenced by several factors:

- **Reactor geometry:** The ratio of the cross-sectional area of the riser to the downcomer (Ad/Ar) is critical for determining the velocity of the liquid circulation. The height-to-diameter ratio, the geometry of the gas-liquid separator, and the bottom clearance also play important roles.
- **Wastewater characteristics:** The concentration and composition of organic and inorganic matter, as well as the flow rate, affect the required mixing and treatment efficiency.
- **Microbial activity:** Factors like temperature, pH, and the concentration and morphology of the microbial biomass (e.g., floc vs. pellet formation) influence biogas production, fluid viscosity, and overall reactor performance.
- **Gas sparger design:** The type, size, and location of the gas sparger affect bubble size, gas holdup, and mass transfer. Smaller bubbles increase the gas-liquid interfacial area and improve transfer efficiency.
- **Hydraulic retention time (HRT):** The time wastewater spends in the reactor is a key operational parameter for determining reactor capacity and efficiency.

- **Simplicity**: It has a simple design with no moving parts, like mechanical stirrers, which reduces maintenance needs and operational complexity.
- **Low energy consumption**: The absence of mechanical agitation leads to lower operational energy costs compared to stirred-tank reactors.
- **Low shear stress**: Gentle mixing is ideal for cultivating microorganisms, such as those that form the delicate granules used in anaerobic digestion.
- **Biogas production**: Anaerobic digestion generates methane-rich biogas, a valuable energy source that can be reused for heating the reactor or generating electricity.
- **Low sludge output**: Anaerobic treatment produces significantly less excess sludge than aerobic systems, which reduces sludge disposal costs.
- **Effective for high-strength waste**: It is particularly well-suited for treating industrial wastewater with high organic loads (high BOD/COD), converting the organic matter into biogas.

Types of airlift bioreactors

The two primary configurations of airlift bioreactors are:

Internal loop ALR: The downcomer is located inside the riser, often as a concentric draft tube. This design is compact but may provide less uniform circulation compared to external loops.

- **External loop ALR:** The downcomer is a separate pipe connected to the outside of the main riser column. This configuration provides a more defined circulation pattern.

Design considerations

Several factors influence the performance and fluid dynamics of an anaerobic ALR.

- **Geometry**: The ratio of the cross-sectional area of the downcomer to the riser is critical for determining the liquid velocity and mixing efficiency.
- **Gas sparger**: The design of the gas distributor affects bubble size and distribution. The smaller the bubbles, the higher the mass transfer.
- **Gas superficial velocity**: The rate of gas injection is the primary operating parameter for controlling liquid circulation, mixing, and mass transfer.
- **Temperature**: The treatment efficiency of anaerobic systems is heavily dependent on temperature. Optimal operation is often achieved at higher, thermophilic temperatures (~55 °C).
- **Hydrodynamics**: Key parameters for optimal design include gas hold-up, liquid circulation velocity, and mixing time.
- **Process control**: Automated systems can monitor and control parameters like pH, temperature, and pressure to maximize efficiency and stability.

Advantages and applications

Airlift bioreactors offer several benefits for anaerobic wastewater treatment compared to conventional systems like continuously stirred tank reactors (CSTRs) and upflow anaerobic sludge blanket (UASB) reactors.

- **Advantages:**
  - Simple, robust design with no moving parts.
  - Low maintenance and operating costs.
  - Energy-efficient mixing using the produced biogas.
  - Effective for treating high-strength wastewater.

- **Applications**

  Anaerobic ALRs have proven effective for treating various types of wastewater. Industrial wastewater treatment, including distillery, dairy, and textile industries. Integrated hybrid systems for removing complex contaminants.

  - **Refinery wastewater**: One pilot-scale study used a functional-microbe-enhanced ALR to achieve stable COD removal and over 50% sludge reduction.
  - **Distillery wastewater**: Anaerobic membrane bioreactors (AnMBRs), which use an airlift design, demonstrated 96.9% COD removal and high methane production from distillery wastewater.
  - **Textile wastewater**: Hybrid airlift reactors have shown high COD removal (up to 75%) and methane production when treating textile wastewater, with efficiency increasing at higher temperatures.
  - **Municipal wastewater**: When combined with membrane filtration, airlift-type anaerobic reactors can effectively treat low-strength municipal wastewater with high COD removal (over 90%) and stable biogas production.

Challenges and considerations

Despite their benefits, anaerobic ALRs present some challenges:

- **Dead zones:** Insufficient mixing can occur, especially in large-scale reactors, leading to "dead zones" where biomass is poorly supplied with nutrients.

- **High biomass density:** High concentrations of microbes can increase fluid viscosity, hindering mass transfer and circulation.

- **Hydrodynamic complexity:** The complex flow behavior of the gas-liquid-solid system can make predicting and modeling key operational parameters difficult.

- **Start-up time:** Anaerobic reactors generally have longer start-up periods compared to aerobic systems.

PACKED BED BIOREACTORS

The term "packed bed bioreactor" refers to an anaerobic fixed-film reactor, where microorganisms attach to a support medium inside a column. These reactors use a fixed, inert packing material to provide a surface for microorganisms to grow as a biofilm, facilitating the degradation of organic matter in wastewater. As wastewater passes through the reactor, the attached biofilm digests the organic matter. This configuration offers high biomass retention, allowing for high treatment efficiency with relatively short hydraulic retention times (HRTs).

Working

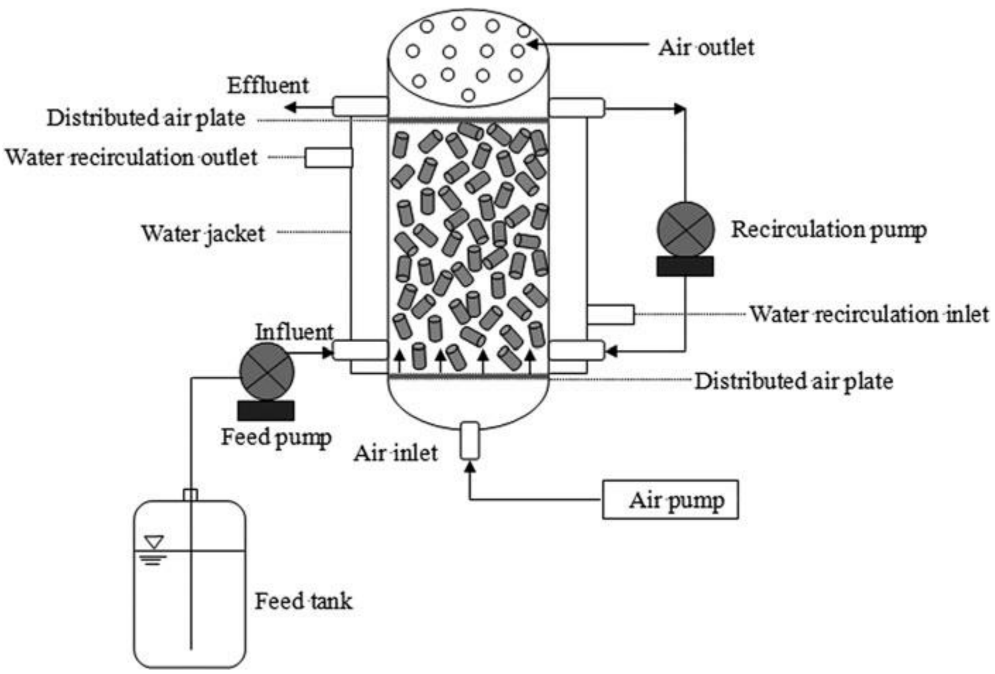
In a packed bed bioreactor (PBR), wastewater flows through a column filled with packing material, or a "bed." Anaerobic microorganisms attach to this media, forming a stable biological film, or biofilm. As the wastewater passes over the biofilm, the microorganisms digest the organic matter, producing biogas (primarily methane and carbon dioxide).

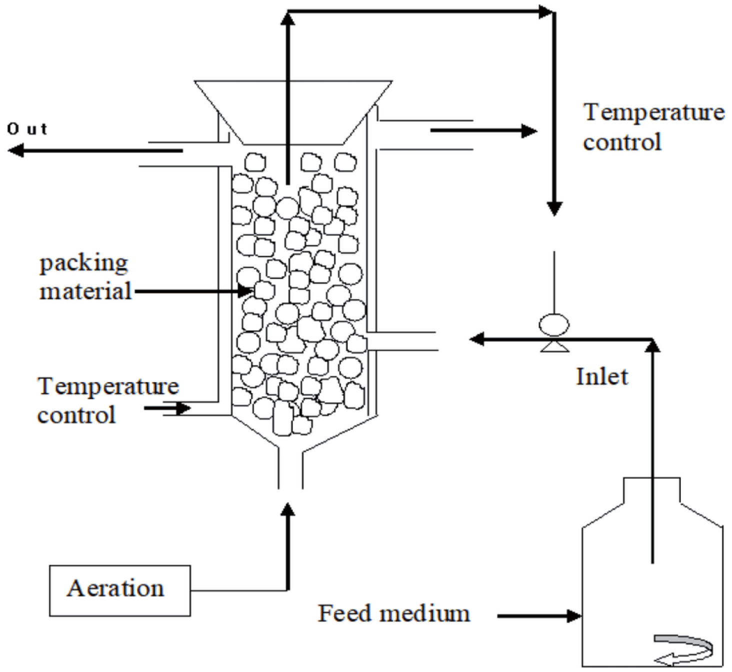
Configurations

- **Upflow anaerobic filter (AF):** In this common configuration, wastewater is fed from the bottom of the reactor, passing upward through the packed media. This flow regime encourages the formation of dense, stable biomass aggregates.
- **Downflow stationary fixed film (DSFF):** Wastewater is fed from the top and flows downward.
- **Two-stage anaerobic process:** For treating more complex wastewaters, systems can use two packed-bed reactors in series. The first reactor is optimized for acidogenesis (producing volatile fatty acids), and the second for methanogenesis (producing methane).

Key components

- **Reactor vessel:** A cylindrical or rectangular tank that contains the packing material and wastewater.
- **Packing media:** Inert support material for biofilm growth. Options include:
  - Plastic media (rings, sheets)
  - Natural materials (gravel, pumice, volcanic rock)
  - Porous synthetic materials (e.g., PVA-gel beads, activated carbon)
- **Inlet and outlet:** Ports for feeding wastewater and discharging treated effluent. For upflow systems, the inlet is at the bottom and the outlet is at the top.
- **Biogas collection:** A system to capture the biogas produced during digestion, which can be used as a source of renewable energy.





Packing materials used for anaerobic packed bed bioreactors

Packed bed bioreactors for anaerobic wastewater treatment use media to support the growth of microbial biofilms. These biofilms are responsible for the anaerobic digestion of organic matter in the wastewater. The choice of packing material is crucial as it significantly affects the reactor's performance, stability, and cost.

Key functions and characteristics

- **Provide a high specific surface area:** A large surface area allows for a greater biomass attachment and retention within the reactor.
- **Offer high porosity:** A high void volume is needed to prevent clogging, channeling, and high-pressure drops, ensuring efficient wastewater and gas flow through the bed.
- **Support microorganism growth:** The material should have surface properties that promote robust and stable biofilm formation.
- **Possess mechanical stability:** The material must be mechanically robust to resist compaction under its own weight and water pressure.
- **Be non-toxic:** The material must not leach any toxic substances that could inhibit the activity of the anaerobic microorganisms.
- **Be cost-effective and available:** The cost and availability of the material are practical considerations, especially for large-scale applications.

Common types of packing materials

1. Synthetic materials (Plastics and polymers)

- **Polyvinyl Chloride (PVC) and polypropylene rings:** Lightweight, cost-effective, and easy to handle and install. Their structured and random shapes, like Raschig rings, provide a high surface area.
- **Polyurethane foam:** Used as a support matrix for microbial immobilization. Offers high porosity, though some types may have less wear resistance than other plastics.
- **Expanded Polystyrene (EPS) beads:** Can be coated to increase hydrophilicity and enhance microbial growth. They are lightweight and have low density, making them suitable for fluidized bed applications.
- **Hollow fiber membranes:** Provide an immobilized system for targeted enzymatic reactions and high biomass retention.

2. Inorganic materials

- **Crushed rock, gravel, and stone:** Traditional, low-cost packing materials. While effective, they have a lower specific surface area and can be heavy.
- **Ceramics:** Available in various forms, like rings, that offer chemical stability and a high specific surface area. They can be more expensive than other options.
- **Expanded clay beads:** Spherical, with a high porosity and suitable surface for cell attachment.
- **Sand and quartz:** Used in some applications, but their small particle size can lead to higher pressure drops and clogging issues.
- **Granular Activated Carbon (GAC):** Offers an extremely high surface area and can also adsorb some organic and inhibitory compounds, but is relatively expensive.

3. Natural/Fibrous materials

- **Coconut coir fiber:** A low-cost, readily available, and durable natural material that can be highly effective. Its coarse, irregular surface promotes microbial growth. It can be used in various configurations, including bottle-brush shapes.
- **Wood chips and wooden blocks:** A lower-cost, natural alternative, though their durability over long periods in an anaerobic environment may vary.
- **Bamboo pieces:** Used as a packing medium, especially in regions where it is readily available.

Factors influencing packing material selection

The optimal packing material depends on several factors related to the specific wastewater treatment application:

- **Type of wastewater:** Wastewaters with high suspended solids are prone to clogging, requiring media with a high porosity and larger pore size.
- **Cost:** The balance between the initial cost of the material and its performance and longevity is a key consideration.
- **Hydraulic loading rate (HLR):** The rate at which wastewater flows through the reactor affects the required porosity and particle size to maintain a low pressure drop.
- **Organic loading rate (OLR):** High OLR requires a packing material that can support a dense, active biofilm.
- **Physical and chemical properties:** Properties such as surface roughness, hydrophilicity, and density play a significant role in biofilm attachment and overall reactor performance.

Operational factors

- **Organic Loading Rate (OLR):** This is the amount of organic material fed into the reactor per unit volume per day. PBRs can handle high OLRs, but excessively high rates can negatively impact methanogenic bacteria, reducing removal efficiency.
- **Hydraulic Retention Time (HRT):** The time wastewater spends in the reactor. Longer HRTs generally lead to better COD removal but decrease the rate of treatment.
- **Temperature:** Mesophilic (around 35°C) and thermophilic temperatures (higher) are typical for anaerobic digestion. Performance can be lower in colder climates unless steps are taken to maintain warmth.
- **pH:** The anaerobic process is sensitive to pH, and it is best maintained between 6.6 and 7.6. Acid-forming bacteria thrive at lower pH, while methane-forming bacteria are inhibited.
- **Microbial community:** Maintaining a healthy balance between acid-forming and methane-forming bacteria is crucial for stable and efficient treatment.

The overall process of anaerobic digestion within a packed bed bioreactor involves four main stages performed by different microbial groups:

1. **Hydrolysis:** Complex organic matter (proteins, carbohydrates, lipids) is broken down into simpler, soluble molecules like sugars and amino acids.
2. **Acidogenesis:** Acid-forming bacteria convert the products of hydrolysis into volatile fatty acids (VFAs), along with hydrogen ($H2$) and carbon dioxide ($CO2$).

3. **Acetogenesis:** Acetogenic bacteria further convert intermediate products like propionate and butyrate into acetate, ($H2$ and $CO2$)
4. **Methanogenesis:** Methane-forming archaea (methanogens) convert acetate and ($H2/CO2$) into methane ($CH4$) and ($CO2$).

The structure of the packed bed supports these biological processes:

- **Support media:** The column is filled with a fixed support material, such as plastic, gravel, or activated carbon, which provides a large surface area for the biofilm to grow.
- **Biomass retention:** The packed media ensures a long solids retention time (SRT) by preventing the washout of slow-growing microorganisms, particularly methanogens, regardless of the wastewater flow rate.
- **Flow pattern:** The wastewater can flow either upward (anaerobic filter) or downward (downflow stationary fixed film) through the packed bed. The upflow configuration helps maintain a quiescent inlet region, promoting the development of dense biomass aggregates.

Design and operating parameters

Optimal performance of an anaerobic packed bed reactor depends on several factors:

- **Hydraulic Retention Time (HRT):** The time wastewater remains in the reactor. A shorter HRT is possible due to the long SRT achieved by the packed bed, but it must be long enough for microorganisms to complete digestion.
- **Organic Loading Rate (OLR):** The amount of organic matter fed to the reactor per unit volume per day. Packed bed reactors can handle high OLRs, making them suitable for concentrated industrial wastewaters.
- **Temperature:** Microbial activity is highly dependent on temperature. The reactor is often operated under mesophilic (30–40 °C) or thermophilic (50–60 °C) conditions.
- **pH:** The ideal pH range for methanogenic bacteria is 6.6–7.6. Sufficient alkalinity is needed to buffer the system against volatile fatty acid accumulation.
- **Nutrient requirements:** Anaerobic treatment requires specific nutrients like nitrogen and phosphorus. These may need to be supplemented, especially when treating industrial wastewater with low nutrient content.

Advantages and disadvantages

Advantages	Disadvantages
High biomass concentration: The fixed film promotes a high density of microbes, leading to a smaller reactor footprint.	**Clogging:** The packed media can become clogged by suspended solids and excess biofilm growth, which can cause high pressure drops and reduce treatment efficiency.
High treatment efficiency: The long contact time between biomass and wastewater results in high chemical oxygen demand (COD) removal rates.	**Flow channeling:** This can occur when water finds preferential paths through the packed bed, reducing contact time and overall treatment effectiveness.
High process stability: The fixed biomass offers good stability against shock loads and fluctuations in influent characteristics.	**Difficult maintenance:** Cleaning, maintaining, or replacing the packing material can be challenging, often requiring the reactor to be shut down.
Simple operation and low maintenance: The reactor has no moving parts (unlike a stirred-tank reactor), resulting in lower operating costs and maintenance.	**Poor temperature control:** The fixed bed can lead to inefficient heat exchange and thermal gradients.
Low sludge production: Anaerobic digestion generates less excess sludge compared to aerobic processes, reducing disposal costs.	**Slow startup:** Developing a sufficiently active and mature biofilm on the support media can take a long time, though using a granular inoculum can speed this up.
Energy production: The process produces methane-rich biogas, which can be recovered and used as a fuel source.	**Potential inhibition:** High concentrations of certain wastewater components, such as sulfides or ammonia, can inhibit methanogenic bacteria.

Applications

Packed bed bioreactors are effective for treating a wide range of industrial wastewaters particularly those with high organic concentrations and soluble organic matter.

- **Food and beverage industry:** Treatment of dairy, brewery, and other food-processing wastewaters.
- **Pharmaceutical and chemical industries:** Handling complex and potentially toxic industrial effluents.
- **Landfill leachate:** Treating leachate, which often contains high organic and nitrogen concentrations.
- **Municipal wastewater:** Pre-treating high-strength municipal wastewater.