Aerobic and Anaerobic Degradation of Aliphatic and Aromatic Compounds

Introduction

Biodegradation is a fundamental biological process in which microorganisms transform complex organic pollutants into simpler and less toxic products. This topic is increasingly important due to the global rise of plastics, pharmaceutical residues, antibiotics, and other emerging contaminants in soil and water ecosystems.

Microorganisms possess unique metabolic pathways enabling them to degrade aliphatic (linear or branched) and aromatic (ring-based) compounds under aerobic and anaerobic conditions.

Types of Organic Pollutants

1- Aliphatic Compounds

A- Linear hydrocarbons (e.g., hexane)
B- Branched hydrocarbons (e.g., isooctane)
C- Alcohols, aldehydes, organic acids
D- Common sources: petroleum spills, industrial waste, plastics

2- Aromatic Compounds

A- Benzene, toluene, xylene, phenols
B- Polycyclic aromatic hydrocarbons (PAHs)
C- Antibiotics and pharmaceutical residues
D- More persistent and toxic due to stable ring structures

Aerobic Degradation

Aerobic degradation requires oxygen as a terminal electron acceptor.

First \\ Aerobic Degradation of Aliphatic Compounds

Microbes use:

- Monooxygenases
- Dioxygenases

Typical steps:

1- Activation (introduction of an –OH group)
2- Conversion into alcohols → aldehydes → fatty acids
3- Entry into β-oxidation pathway
4- Complete mineralization into CO_2 + H_2O

Microorganisms involved

1- Pseudomonas
2- Rhodococcus
3- Alcanivorax (marine oil degraders)

Second \\ Aerobic Degradation of Aromatic Compounds

Requires oxygenase enzymes to break the aromatic ring.

Steps:

1- Ring hydroxylation → catechol formation
2- Ring cleavage
3- Ortho pathway: produces succinate + acetyl-CoA
4- Meta pathway: produces pyruvate + acetaldehyde

Key Microbes:

1- Pseudomonas putida
2- Burkholderia cepacia

Anaerobic Degradation

Occurs in environments lacking oxygen such as sediments, groundwater, sludge digesters.

First \\ Anaerobic Degradation of Aliphatic Compounds

Microbes use alternative electron acceptors:

1- Nitrate
2- Sulfate
3- Iron (III)
4- CO_2 (methanogenesis)

Mechanisms:

1- Fumarate addition
2- Hydrogenation
3- Carboxylation

Important microbial groups:

1- Sulfate-reducing bacteria (Desulfovibrio)
2- Methanogens (Methanosaeta, Methanobacterium)
3- Nitrate reducers (Thauera)

Second \\ Anaerobic Degradation of Aromatic Compounds

More challenging because the ring structure is stable without oxygen.

Mechanisms:

1- Carboxylation of aromatic ring
2- Benzoyl-CoA pathway (central anaerobic pathway)
3- Reductive dearomatization → ring cleavage

This produces acetate, CO_2, CH_4 depending on the terminal electron acceptor.

Microbial Interaction with Plastics

Plastics, especially polyethylene (PE), polypropylene (PP), polystyrene (PS), and PET, are highly resistant to degradation.

Aerobic Degradation of Plastics

Occurs via:

1- Surface oxidation (UV/thermal aging increases microbial attack)
2- Enzymatic depolymerization:
3- PETase
4- MHETase

Microbes able to degrade plastics:

1- Ideonella sakaiensis (PET degradation)
2- Rhodococcus ruber
3- Bacillus subtilis
4- Certain fungi: Aspergillus, Penicillium

Anaerobic Degradation of Plastics

Slower and less efficient.

1- Occurs in landfills and anaerobic digesters.
2- Involves hydrolysis → fermentation → methanogenesis.
3- Produces CH_4 and CO_2 as end products.

Microbial Interaction with Antibiotics

Antibiotics in wastewater pose serious ecological risks:

1- Development of resistant bacteria
2- Toxicity to microbial communities

Microorganisms can degrade antibiotics through:

1- Hydrolysis
2- Oxidation–reduction reactions
3- Enzymatic cleavage of β-lactam, macrolide, or quinolone structures
4- Cometabolism (degradation of antibiotic only when another substrate is present)

Examples:

1- Sphingomonas → quinolone degradation
2- Actinobacteria → tetracycline degradation
3- Bacillus species → β-lactam degradation

Emerging Pollutants

Includes:

1- Microplastics
2- Personal care products
3- Hormones
4- Flame retardants
5- Heavy metals–organic complexes

Microbial strategies:

1- Biosorption
2- Bioaccumulation
3- Enzymatic breakdown
4- Reductive transformation
5- Oxidative enzymes (laccases, peroxidases)

Environmental and Biotechnological Applications

Wastewater treatment

1- Activated sludge systems
2- Trickling filters
3- Anaerobic digesters
4- Biofilm reactors (MBBR)

Bioremediation

1- Soil cleaning
2- Oil spill remediation
3- Plastic biodegradation
4- Removal of pharmaceutical wastes

Synthetic Biology Approaches

1- Engineered microbes with enhanced degradation pathways
2- Enzyme redesign (e.g., improved PETases)
3- Microbial consortia for complex pollutant mixes