MODULE-5

Green Materials and E-Waste Management

Green Chemistry: Introduction, properties and applications of green solvents for server heat management. Synthesis and properties of glycerol trioleate ester and its uses in IT infrastructure applications. Green synthesis of ZnO nanoparticles and its uses in magnetic Radio Frequency Identification (RFID) and Internet of Nano Things (IONT) system applications.

Biomaterials: Introduction, synthesis and properties of polylactic Acid (PLA) and polyethylene glycol (PEG) and its uses in touch screen applications. Synthesis and properties of Alginate Hydrogel and its uses in Brain-Computer Interfaces (BCIs) applications.

E-waste: Introduction, sources, composition of e-waste, effects of e-waste on environment and human health, Artificial intelligence in e-waste management, extraction of gold from e-waste by bioleaching method.

Define waste.

Waste refers to any material that is not wanted or needed and is discarded or disposed of.

Classification of Waste:

Waste can be classified into several categories including household waste, industrial waste, hazardous waste, and e-waste (waste from electronic devices).

Define waste management.

Waste management refers to the collection, transportation, treatment, and disposal of waste materials to reduce their negative impact on the environment and human health.

Define E-waste management.

E-waste management refers to the processes and systems used to collect, transport, treat, and dispose of electronic waste (e-waste) in an environmentally responsible and safe manner.

Sources of electronic waste (e-waste):

The main sources of electronic waste (e-waste) include:

- Household Appliances: Refrigerators, washing machines, microwaves, vacuum cleaners, irons, air conditioners, and dishwashers.
- IT and Telecommunication Devices: Computers, laptops, printers, smartphones, tablets, and other communication devices.
- Consumer Electronics: Televisions, DVD players, cameras, video game consoles, stereos, and other entertainment devices.

- Office Equipment: Printers, photocopiers, scanners, fax machines, and other office machinery.
- Lighting Equipment: Fluorescent lamps, LED bulbs, and other lighting devices.
- Medical Devices: Monitoring instruments, diagnostic machines, pacemakers, defibrillators, and other medical equipment.
- Industrial Equipment: Motors, pumps, transformers, and other machinery used in industry.
- Electrical and Electronic Tools: Power drills, saws, gardening tools, and similar electronic tools.
- Toys and Recreational Devices: Electronic toys, video game consoles, and electronic musical instruments.
- Chargers and Batteries: Non-functional or obsolete chargers and batteries from various devices.

Composition of e-waste:

- Metals: E-waste contains valuable metals such as copper, gold, silver, aluminum, ferrous metals (iron and steel), and special metals like cobalt, indium, tin, and antimony.
- Plastics: Many electronic devices include plastic components such as casings, insulation, and cables, constituting about 21% of e-waste.
- Glass: Found mainly in screens, lenses, and cathode ray tubes (CRTs).
- Circuit boards: Printed circuit boards (PCBs) contain a complex mixture of metals and hazardous substances.
- Batteries: Contain hazardous materials such as lead, mercury, cadmium, lithium, nickel, and cobalt.
- Hazardous materials: Include heavy metals (lead, mercury, cadmium, arsenic, beryllium, hexavalent chromium), flame retardants (brominated flame retardants), polychlorinated biphenyls, and other toxic chemicals.
- Other materials: Components of ceramics, rubber, wood, plywood, and concrete found in some electronic devices.

Effects of E-Waste on Environment and Human Health

- **Soil contamination:** Toxic metals (lead, cadmium, mercury) seep into soil, reducing fertility and entering the food chain.

- **Water pollution:** Leaching of heavy metals and acids contaminates groundwater and surface water sources.
- **Air pollution:** Open burning of plastics and circuit boards releases dioxins, furans, and other harmful gases.
- **Loss of biodiversity:** Toxic chemicals harm aquatic life, plants, and animals, disrupting ecosystems.
- **Resource depletion:** Failure to recycle valuable metals increases dependence on mining.

On Human Health

- **Neurological damage:** Lead and mercury exposure affects brain function, especially in children.
- **Respiratory issues:** Inhalation of toxic fumes from burning e-waste causes lung diseases and breathing problems.
- **Kidney and liver damage:** Cadmium and other metals accumulate in vital organs, impairing their function.
- **Cancer risk:** Long-term exposure to carcinogenic substances like dioxins, arsenic, and brominated flame retardants.
- **Reproductive and developmental disorders:** Toxic chemicals affect fertility, pregnancy, and child development.
- **Skin and eye irritation:** Direct contact during informal recycling causes rashes, burns, and eye problems.

Artificial Intelligence (AI) in E-Waste Management (Chemistry Perspective)

- **Identification of hazardous chemicals**: AI tools detect and classify toxic chemicals such as lead, mercury, cadmium, and brominated flame retardants in e-waste using advanced sensor data and pattern recognition.
- **Chemical composition analysis:** Machine learning models process spectral data (XRD, XRF, FTIR) to rapidly determine the composition of metals, plastics, and semiconductors, enabling targeted recycling.
- **Intelligent sorting and separation:** AI-driven robotic systems utilize chemical property data (conductivity, density, magnetic behavior) to efficiently separate recyclable metals from hazardous or non-recyclable substances.

- **Prediction of toxic leaching:** AI predicts the leaching behaviour of chemicals from e-waste into soil and water, supporting the design of eco-friendly chemical treatments and containment strategies.
- **Optimization of recycling processes:** Algorithms recommend green chemical methods such as bioleaching and solvent extraction for efficient recovery of valuable metals like gold, copper, and palladium.
- **Environmental impact monitoring:** AI models continuously track chemical pollution levels in air, water, and soil around e-waste sites, ensuring compliance with environmental safety standards.
- **Waste-to-resource conversion:** AI supports chemical upcycling, transforming hazardous e-waste materials into valuable products such as nanomaterials and catalysts.
- **Data-driven policy and management:** AI systems provide actionable insights for policymakers to regulate toxic chemical disposal and promote sustainable, advanced recycling technologies.

Extraction of Gold from E-Waste by Bioleaching:

Bioleaching is a sustainable and eco-friendly technique that uses microorganisms to recover gold from electronic waste, replacing toxic chemical-intensive methods.

Pre-treatment of E-Waste: Printed circuit boards and gold-plated parts are shredded and pulverized to increase surface area. Chemical leaching with nitric/sulfuric acid and hydrogen peroxide removes base metals like copper, nickel, and zinc that interfere with gold dissolution.

Microbial Culture Preparation: Cyanogenic bacteria such as *Chromobacterium violaceum* or *Pseudomonas aeruginosa* are cultured under optimized pH, temperature, and nutrient conditions. These microbes enzymatically convert substrates (e.g., glycine) into hydrogen cyanide (HCN), which dissociates into cyanide ions (CN^-).

Microbial cyanide generation: $C_2H_5NO_2 + O_2 \rightarrow HCN + CO_2 + H_2O$

Bio-Cyanidation (Two-Step Leaching):

- **Step 1:** Microbes are grown until exponential phase to maximize cyanide production.
- **Step 2:** The spent culture medium (rich in CN^-) is separated and added to pre-treated e-waste. This indirect contact avoids microbial exposure to toxic heavy metals.

Gold Leaching Reaction: Cyanide ions dissolve metallic gold in the presence of oxygen, forming a stable dicyanoaurate complex:

$$4Au + 8CN^- + O_2 + 2H_2O \rightarrow 4[Au(CN)_2]^- + 4OH^-$$

Recovery of Gold: Gold is recovered from the leachate by zinc cementation, activated carbon adsorption, or electrowinning, followed by refining to pure metal.

GREEN CHEMISTRY:

Introduction to Green Chemistry

Green chemistry focuses on designing chemical products and processes that **reduce or eliminate hazardous substances**, promoting sustainability, environmental safety, and energy efficiency.

Introduction to Green Solvents:

Green solvents are **environmentally benign liquids** used to dissolve substances or facilitate chemical processes without harming humans or ecosystems. They aim to replace hazardous organic solvents with safer alternatives

- **Water** – the ultimate green solvent.
- **Supercritical fluids** – like supercritical CO_2 for efficient heat transfer.
- **Ionic liquids (ILs)** – tunable, non-volatile, and thermally stable.
- **Bio-based solvents** – derived from renewable feedstocks like glycerol or ethyl lactate.

Properties of Green Solvents for Server Heat Management

For modern server cooling and data center thermal management, green solvents must have specialized properties:

1. High Thermal Conductivity & Heat Capacity – Efficiently absorb and transfer heat from CPUs, GPUs, and other components.

2. Low Viscosity – Ensures smooth circulation in cooling systems with minimal energy consumption.

3. Electrical Non-Conductivity – Prevents short circuits when in contact with electronics.

4. Chemical & Thermal Stability – Resistant to degradation at high temperatures; protects hardware from corrosion.

5. Non-Toxic & Biodegradable – Safe for humans and the environment, reducing risk in case of leaks.

6. Freeze & Boil Point Stability – Maintains performance under varying operating temperatures.
7. Leak Detection Capability – Some solvents are dyed or fluorescent for easy monitoring.

Examples: Propylene glycol-based fluids, silicone-based immersion fluids, and specially formulated ionic liquids. These are engineered to be compatible with metals like aluminum, copper, and steel in server hardware.

Green Solvents Applications in Server Heat Management:

Green solvents are revolutionizing **data centre cooling** through advanced technologies:

- **Direct Liquid Cooling (DLC):** Solvents circulate directly over CPUs, GPUs, and power components, removing heat efficiently and reducing energy consumption.
- **Immersion Cooling:** Entire servers are submerged in non-conductive green solvents, enabling higher server density, uniform cooling, and reduced infrastructure footprint.
- **Hybrid Cooling Systems:** Combines air and liquid cooling using green solvents to optimize thermal efficiency and energy use.
- **Sustainable Operations:** Green solvents with **low global warming potential (GWP)** and **zero ozone depletion potential (ODP)** help achieve eco-friendly, carbon-neutral data center operations.

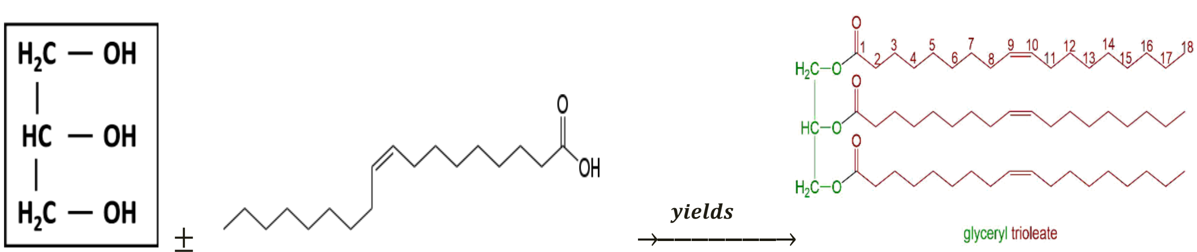
Synthesis and properties of glycerol trioleate ester and its uses in IT infrastructure applications.

Synthesis of Glycerol Trioleate

on esterification reaction between glycerol (a triol) and oleic acid (a fatty acid) in presence of acid catalyst (e.g., p-toluenesulfonic acid or H_2SO_4) under heat 140–220°C to form Glycerol Trioleate

Chemical Reaction:

$$C_3H_8O_3 + 3\,C_{18}H_{34}O_2 \xrightarrow[\text{Heat}]{\text{Acid Catalyst}} C_{57}H_{104}O_6 + 3\,H_2O$$



Properties of glycerol trioleate:

Property	Value / Description
Physical state	Oily liquid at room temperature
Melting point	~−5.5 °C
Solubility	Insoluble in water, soluble in organic solvents
Major natural source	Olive oil (4–30%)
Biological role	Food, research, "Lorenzo's oil"
Combustion reaction	$C_{57}H_{104}O_6 + 80\ O_2 \rightarrow 57\ CO_2 + 52\ H_2O$
Heat of combustion	8,389 kcal/mol (35,100 kJ/mol)

Uses in IT Infrastructure Applications

- **Green Dielectric Coolant**: Used as a non-toxic insulating liquid in data centre transformers and server cooling systems. Prevents short circuits and improves heat dissipation.
- **High-Temperature Lubricant for Hardware**: Can act as a biodegradable lubricant for mechanical components like hard disk drives or server fans.
- **Phase Change Cooling Media**: With high thermal stability, used in immersion cooling of CPUs and GPUs to maintain optimal temperatures. Reduces thermal hotspots in high-performance computing.
- **Fire-Safe Alternative to Mineral Oils**: Low flammability makes it a safer alternative for liquid cooling in server racks.
- **Eco-Friendly Thermal Management**: Being biodegradable and non-toxic, it minimizes environmental hazards in IT facility maintenance.
- **Enhanced Reliability of Electronics**: Reduces thermal stress on sensitive ICs, prolonging the lifespan of critical infrastructure.

Green Solution Combustion Synthesis of ZnO Nanoparticles and its uses in magnetic Radio Frequency Identification (RFID) and Internet of Nano Things (IONT) system applications.

Solution combustion synthesis (SCS) is a rapid and energy-efficient route for producing zinc oxide (ZnO) nanoparticles. The process becomes greener when sugarcane juice is used as the fuel.

Sugarcane juice contains sucrose, glucose, and fructose, which act as natural reducing and complexing agents. During combustion, these sugars decompose to release gases (CO_2, H_2O), creating porosity and leaving ZnO nanoparticles as the final product.

- Dissolve 3.65g of zinc nitrate hexahydrate [$Zn(NO_3)_2 \cdot 6H_2O$] in distilled water.

$$Zn(NO_3)_2 \rightarrow Zn^{2+} + 2NO_3^-$$

- Add 7.3 ml Sugarcane juice typically has ~12% w/v sugar in the stoichiometric fuel-to-oxidizer ratio. For sucrose ($C_{12}H_{22}O_{11}$) as the main fuel:
- Stir and ultrasonicate the solution for 30 minutes to form a homogeneous mixture.
- Heat gently at ~80–90 °C until a viscous gel forms.
- Place the gel in a preheated furnace (300–600 °C).
- Combustion occurs spontaneously, producing flame and froth as gases (CO_2, H_2O, N_2) evolve.
  - $24\ Zn(NO_3)_2 \cdot 6H_2O + 5\ C_{12}H_{22}O_{11} \rightarrow 24\ ZnO + 60\ CO_2 + 199\ H_2O + 24\ N_2$

  (i.e., 24 mol $Zn(NO_3)_2$ requires 5 mol sucrose).
- Cool to obtain porous ZnO ash.
- Calcine the powder at 400–500 °C for 2–3 h to remove carbon residues and enhance crystallinity.

ZnO Nanoparticles in Magnetic RFID

Magnetic Properties: Doping ZnO with Fe, Ni, or Co induces room-temperature ferromagnetism.

Enhanced Data Storage: Magnetic ZnO allows higher data density and non-volatile memory in RFID tags.

Improved Security: Magnetic behavior makes RFID tags harder to clone or tamper with.

Sensor Integration: ZnO NPs can detect gases, chemicals, or temperature changes for smart RFID tags.

Chipless & Passive Tags: ZnO/metal oxide nanocomposites (e.g., ZnO/TiO_2) enable passive sensing RFID systems.

Miniaturization & Flexibility: Nanoparticle form allows small, flexible, and wearable RFID tags.

ZnO Nanoparticles in Internet of Nano Things (IoNT)

Nanoscale Sensing: High surface area and semiconducting properties enable sensitive detection of environmental or biomedical signals.

Energy Harvesting: Piezoelectric ZnO nanowires or NPs provide self-powered IoNT devices.

Flexible Electronics: ZnO NPs support durable, bendable nanosensors for health monitoring or smart infrastructure.

Targeted Biomedical Applications: Magnetic ZnO NPs can deliver drugs or monitor health internally.

Autonomous Networks: Magnetic interactions help self-assembly of nanosensor networks.

Cost-effective Large-scale IoNT: Enables **distributed sensing systems** for industrial, environmental, and medical applications.

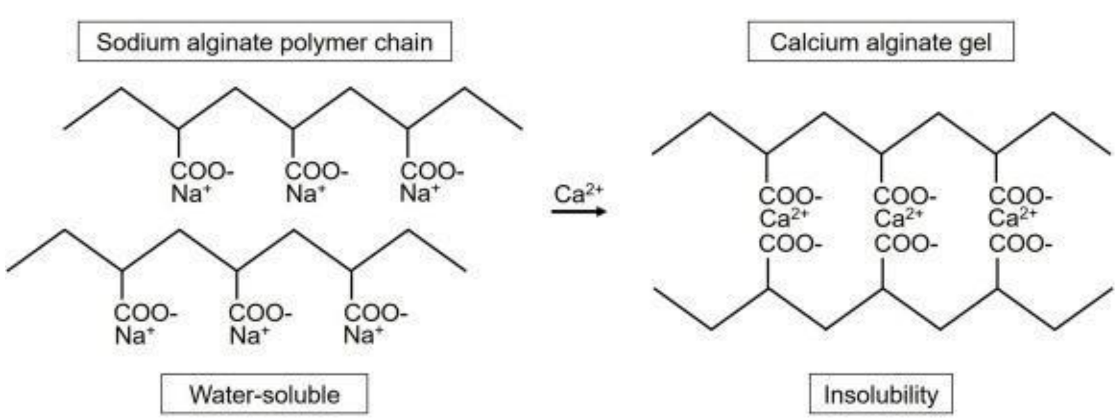
Biomaterials / Biodegradable polymers:

Biomaterials are materials—natural or synthetic—engineered to interact with biological systems for medical, industrial, or technological applications. They are used in implants, drug delivery systems, tissue engineering, and electronic devices.

Synthesis and properties of Alginate Hydrogel and its uses in Brain-Computer Interfaces (BCIs) applications.

Synthesis of Alginate Hydrogel (Ionotropic Gelation)

- **Starting Material**: Sodium alginate, a linear polysaccharide from brown seaweed. Composed of β-D-mannuronic acid (M) and α-L-guluronic acid (G) units.
- **Dissolution**: Sodium alginate is dissolved in water to form a viscous polymer solution.
- **Cross-linking**: A solution of divalent cations, typically $CaCl_2$, is added. Calcium ions (Ca^{2+}) replace sodium ions (Na^+) in G-blocks of alginate chains.
- **Gelation**: Ionic bridges form between polymer chains, entrapping water. Results in a stable, 3D hydrogel network. Described by the "egg-box model", where Ca^{2+} fits into cavities of G-blocks.



Chemical Reaction

$$2Na(Alg) + CaCl_2 \rightarrow Ca(Alg)_2 + 2NaCl$$

Properties of Alginate Hydrogel

- **Biocompatibility & Biodegradability**: Supports cell adhesion and growth.
- **High water content & Porosity**: Facilitates nutrient and ion transport.
- **Ionic Conductivity**: Hydrated ions allow electrical signal conduction.
- **Tissue-like Mechanical Properties**: Soft, flexible, tunable stiffness.
- **Low Immunogenicity**: Minimal inflammatory response; resistant to protein adsorption.
- **Electrochemical Adaptability**: Can form conductive composites with polymers/nanoparticles.

Applications in Brain-Computer Interfaces (BCIs)

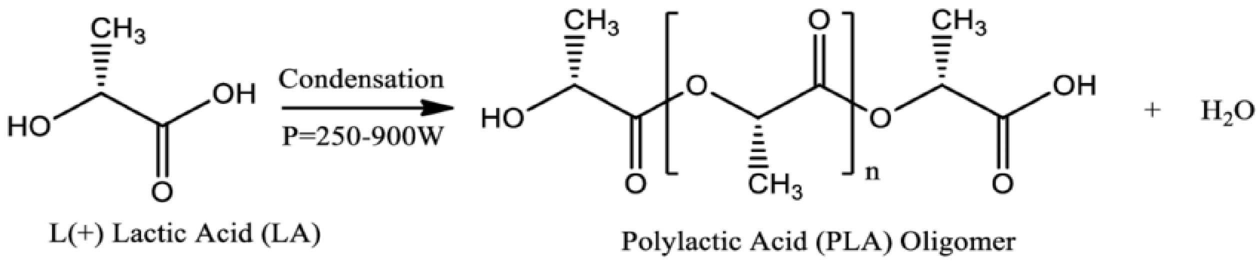
- **Soft Electrode Interface**: Conforms closely to brain tissue, reducing inflammation and motion artifacts.
- **Signal Enhancement**: Ionic conductivity and integration with conductive materials improve **signal-to-noise ratio (SNR)** for electrophysiological recordings.
- **Chronic Implant Stability**: Supports long-term recording by reducing tissue scarring and immune response.
- **Flexible, Implantable Electrodes**: Used in **electrocorticography (ECoG)** and **local field potential (LFP)** recording.
- **Hybrid Hydrogel Systems**: Can incorporate conductive polymers/nanoparticles to enhance electrical properties while maintaining softness.
- Can be engineered for **transparency**, enabling optical and electrical monitoring.

Polylactic Acid (PLA)

- PLA is one of the most promising biopolymers produced from non-toxic, renewable, and naturally occurring lactic acid.
- It is a thermoplastic polymer with good mechanical strength, high biocompatibility, and biodegradable properties.
- Lactic acid is obtained by fermentation of sugars from renewable sources like sugarcane, maize, or tapioca.

Synthesis of PLA

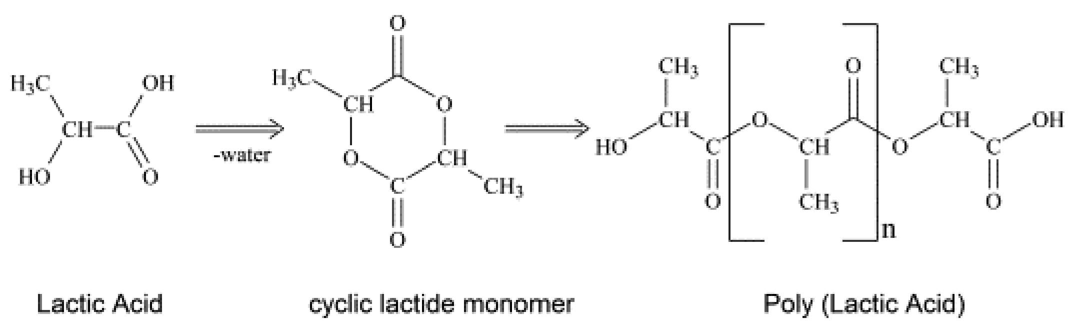
1. Direct Polycondensation of Lactic Acid



2. Ring-Opening Polymerization of Lactide (Preferred)

- Step 1: Formation of Lactide (Cyclic Dimer of Lactic Acid)
- Step 2: Polymerization of Lactide

Produces Low molecular weight polymers



- Produces **high molecular weight PLA** with controlled properties.

Properties of PLA

- Linear, thermoplastic polymer with ~37% crystallinity.
- Glass transition temperature: 50–80 °C
- Melting point: 170–180 °C
- Mechanical properties: Good tensile strength; can be processed into fibres.
- Solubility: Soluble in chlorinated solvents, dioxane, benzene, and THF.
- Biodegradable and biocompatible, suitable for human contact applications.

Uses of PLA in Touch Screen Applications

- Flexible Substrate: PLA films can be used as a lightweight, flexible substrate for touch screens.

- Eco-friendly Material: Reduces environmental impact compared to petroleum-based plastics.
- Protective Coating: Transparent PLA coatings improve scratch resistance.
- Printable Surface: PLA allows for easy deposition of conductive layers (like ITO or silver nanowires) for capacitive touch sensors.
- Biocompatibility: Safe for devices with frequent human contact.

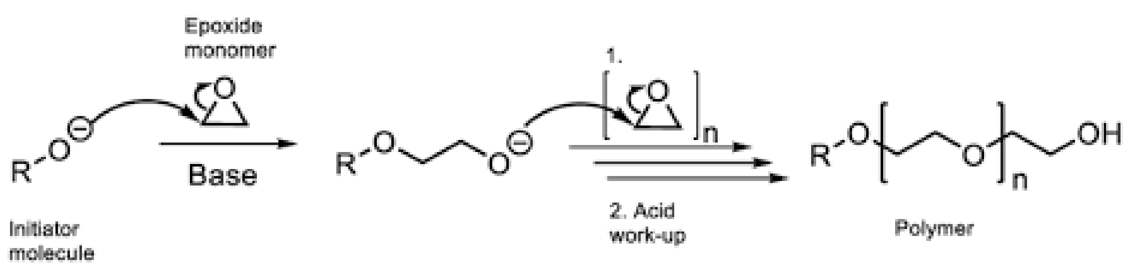
Polyethylene Glycol (PEG)

1. **Introduction:** PEG is a hydrophilic polymer made from ethylene oxide. Known for solubility in water and organic solvents, biocompatibility, and flexibility. Used in pharmaceuticals, cosmetics, medical devices, and electronics.

2. Synthesis of PEG

A. Ring-Opening Polymerization of Ethylene Oxide:

The initiator (water or alcohol) attacks the strained ethylene oxide ring in presence of NaOH or KOH as catalyst, opening it and forming an active alkoxide site. This active site repeatedly attacks additional ethylene oxide monomers, extending the polymer chain until termination, yielding hydroxyl-terminated linear PEG.



3. **Properties of PEG:**

- **Hydrophilic polymer**, soluble in water and many organic solvents.
- **Flexible chain**; low glass transition temperature (~ -60°C).
- **Melting point:** Depends on molecular weight (solid for high MW, liquid for low MW).
- **Non-toxic, biocompatible, and chemically stable.**
- **Low viscosity** for low molecular weight PEG; high viscosity for high molecular weight PEG.

4. **Uses of PEG in Touch Screen Applications:**

- **Flexible Coatings:** PEG can be used as a **transparent, flexible layer** to protect touch screens.
- **Anti-fouling Coatings:** Prevents fingerprint smudges and dust accumulation.
- **Surface Modifier:** Enhances **adhesion of conductive layers** (ITO, silver nanowires) on flexible substrates.
- **Hydrophilic Layer:** Improves moisture management in flexible or foldable touch panels.
- **Electrolyte Component:** Used in **solid polymer electrolytes** for capacitive touch sensors and flexible electronics.