

## Subtopics Innovation Challenge 2026: Sustainable Chemistry and Electronics

### 1. Innovation in Design & Performance

- a. Applying Eco-design principles: designing electronics for durability, repairability, recyclability, and modularity with focus on chemical and materials innovation
- b. Design for disassembly: using adhesives, coatings, and encapsulants that can be safely removed or chemically dissolved.
- c. Reducing material intensity while maintaining performance.
- d. Developing more sustainable solders, recyclable encapsulants, and solvent systems for safer assembly/disassembly.

### 2. Innovations providing more resource efficient use or substitution of critical raw materials and toxic metal species

- a. Alternative technologies for scarce and critical elements and critical nonrenewable resources (see Annex I a.) for details)
- b. Use of abundant, non-toxic, recycled /recyclable feedstocks

### 3. Sustainable Manufacturing Approaches

- a. Low-energy, low-waste fabrication methods (solution processing, additive manufacturing, green solvents).
- b. Designing scalable, safer chemical routes generating less waste
- c. Sustainable alternatives to hazardous reagents and byproducts (including additional technologies) (see Annex I b.) for details)
- c. Development of biodegradable electronics components using polymers and organic materials.
- d. Addressing social issues including child labor, unsafe working conditions, and other forms of injustice.

### 4. End-of-Life & Circularity

- a. Chemical methods for disassembly, selective separation, and recycling
- b. E-waste recycling and recovery of valuable materials
  - i. Electrochemical recycling of materials in electronics (e-waste recovery of metals like Li, Co, Au).
  - ii. Mechanical or chemical recycling of plastic materials in electronics
- c. Use of recyclable, biodegradable<sup>1</sup> materials or materials that undergo full mineralization at end of life
  - i. E.g. biomaterials based, biodegradable conductors and semiconductors.
- d. Closed-loop systems
- e. Prevention of material dissipation<sup>2</sup>

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<sup>1</sup> Biodegradation products should be well-characterized and understood. Ideally, these products should **break down into simple, naturally occurring compounds** that integrate harmlessly into ecosystems or at least be **non-toxic, environmentally safe**, and **do not accumulate** in soil, water, or living organisms. Knowledge of these degradation pathways helps prevent unexpected environmental impacts and supports sustainable chemical use.

<sup>2</sup> The smaller the amount of a given material used in a product, the more difficult it becomes to recover it later. Strategies aimed at reducing material usage may seem more sustainable at first, as they decrease immediate demand. However, this approach can be less sustainable in the long term, especially if technologies for effective recovery do not exist.

When materials are present only in tiny amounts within complex mixtures of multiple materials, elements, or substances, their recovery becomes technically challenging or even impossible. Therefore, while reducing material usage can provide short-term benefits, it may inadvertently lead to greater material dissipation and environmental impact over time. A truly sustainable approach should balance material reduction with the feasibility of recovery, ensuring that long-term circularity is achievable.

## **5. Alternative & Emerging Materials**

- a. Organic and polymer electronics
- b. Advanced Materials for Electronics
  - i. 2D materials like graphene, MoS<sub>2</sub>, and MXenes: Surface chemistry affects electronic and mechanical properties.
  - ii. Metal–organic frameworks (MOFs) and covalent-organic frameworks (COFs): Used in sensing, energy storage, and optoelectronic devices.
  - iii. Self-healing or stimuli-responsive materials for flexible electronics
- c. Sustainable alternatives to fossil-based plastic materials used in electronics, e.g.:
  - i. PVC for cables, insulation, flexible parts
  - ii. ABS for casings for computers, printers, TV's, keyboards, etc.
  - iii. PS for insulation
  - iv. PC for optical discs, lenses, protective covers, LED

## **6. Novel devices**

- a. More sustainable Energy Storage & Conversion Devices (Batteries, Supercapacitors, Fuel Cells)
- b. Organic Electronics, Photonics & Optoelectronics (OLEDs, OPVs, Perovskite solar cells, Photocatalytic devices )

## **ANNEX I**

- a) Critical elements and toxic metal species to be substituted
- i. Rare earth elements: neodymium, dysprosium, terbium for magnets, displays, lasers.
  - ii. Indium: indium tin oxide (ITO) for transparent conductive films.
  - iii. Gallium: GaAs, GaN semiconductors for LEDs, power electronics.
  - iv. Cobalt for lithium-ion battery cathodes.
  - v. Lithium & nickel as battery materials under increasing demand.
  - vi. Tantalum for capacitors.
  - vii. Tin for solders (Sn-based alloys), often from conflict regions.
  - viii. Platinum group metals (PGMs) for catalysts and sensors.
  - ix. Lead (Pb): historically used in solders, glass, and ceramics (restricted by RoHS, but exemptions remain).
  - x. Mercury (Hg) for displays, switches, fluorescent backlights.
  - xi. Cadmium (Cd): CdTe and CdS in thin-film solar cells, quantum dots, pigments.
  - xii. Chromium VI (Cr<sup>6+</sup>) for corrosion protection, plating.
  - xiii. Beryllium for connectors and thermal management (toxic if inhaled)
  - xiv. Silicon/silicone: e.g. semiconductors, transistors and microchips, silicone rubber and sponge for sealing inner circuits and processors to protecting them from heat, corrosion, moisture, and other conditions
- b) Commonly used materials and chemicals to be substituted
- i. Brominated and polybrominated flame retardants (PBDEs, TBBPA, etc.) for circuit boards, plastics (persistent, bioaccumulative).
  - ii. Phthalates: plasticizers in cables and casings (endocrine disruptors).
  - iii. Strong acids and bases: HF, HNO<sub>3</sub>, H<sub>2</sub>SO<sub>4</sub> (etching, cleaning).
  - iv. Chlorinated solvents: trichloroethylene (TCE), dichloromethane (degreasing, cleaning).
  - v. N-methyl-2-pyrrolidone (NMP): solvent in battery and photoresist processing (toxic to reproduction).
  - vi. Dimethylformamide (DMF), dimethylacetamide (DMAc): solvents for polymer processing.
  - vii. Per- and polyfluoroalkyl substances (PFAS): in photoresists, lubricants, and coatings (persistent “forever chemicals”).
  - viii. Cyanides: electroplating of gold and other metals.
  - ix. Phthalates (e.g. Di(2-ethylhexyl) phthalate (DEHP), Dibutyl phthalate (DBP), Benzyl butyl phthalate (BBP), Diisononyl phthalate (DINP))

## Supplementary materials & notes

### Flame Retardants in Electronics

| Category  | Conventional Chemicals          | Problems  | Sustainable Alternatives  | Benefits of Alternatives  |
|---|---------------------------------|---|---|---|
| <b>Brominated flame retardants (BFRs)</b>           | PBDEs (penta, octa, deca), HBCD | Persistent, bioaccumulative, toxic, release dioxins/furans during e-waste burning | <b>Phosphorus-based</b> (phosphates, phosphonates, phosphinates), <b>nitrogen-based</b> systems | Lower toxicity, reduced persistence, effective flame suppression        |
| <b>TBBPA (tetrabromobisphenol A)</b>                | Widely used in PCBs             | Endocrine disruption potential, leaching  | <b>Reactive phosphorus flame retardants, intumescent systems</b>                                | Chemically bound → less leaching, can be integrated into polymer matrix |
| <b>Additive BFRs (plastic housings, connectors)</b> | Mixed brominated organics       | Easily migrate from polymer, contamination in recycling streams                   | <b>Mineral fillers</b> (aluminum hydroxide, magnesium hydroxide, expandable graphite)           | Inert, non-toxic, improve recyclability                                 |

### Phthalates in Electronics

| Category                                 | Conventional Chemicals             | Problems   | Sustainable Alternatives  | Benefits of Alternatives                                |
|--|------------------------------------|--|---|---|
| <b>High-volume plasticizers in PVC</b>   | DEHP, DBP, BBP, DINP, DIDP         | Endocrine disruption, reproductive toxicity, not bound → leach into air/dust | <b>Adipates, sebacates, terephthalates</b>                                      | Lower toxicity, better safety profile                   |
| <b>General cable/plastic flexibility</b> | DEHP in wires, connectors, casings | Banned under EU RoHS, still used elsewhere                                   | <b>Citrate esters</b> (e.g., tributyl citrate, acetyl tributyl citrate)         | Bio-based, biodegradable, safe for contact applications |
| <b>PVC-based components</b>              | PVC + phthalates                   | Recycling difficulty, chlorine → dioxins when burned                         | <b>PVC-free polymers</b> (polyethylene, polypropylene, TPU, bio-based plastics) | Halogen-free, recyclable, less toxic lifecycle          |

### Solvents used in electronics

| Solvent                             | Toxicity  | Hazards  | Environmental Risks                             | Purpose / Application   | Example Products                                     |
|-------------------------------------|---|--|---|---|--|
| <b>Acetone</b>                      | Low to moderate; irritation, CNS effects at high exposure             | Highly flammable; skin and eye irritant                        | VOC; contributes to air pollution               | Cleaning and degreasing of components, removing flux residues | PCBs, semiconductor wafers, connectors               |
| <b>Isopropyl Alcohol (IPA)</b>      | Low; skin and eye irritation, CNS effects at high concentration       | Flammable; irritant  | VOC; biodegradable                              | Cleaning PCBs, removing flux and residues                     | Smartphones, laptops, circuit boards, displays       |
| <b>Toluene</b>                      | Moderate; CNS effects, respiratory irritation                         | Highly flammable; toxic by inhalation and skin absorption      | VOC; toxic to aquatic life                      | Solvent for adhesives, coatings, and photoresists             | LEDs, IC packages, flexible electronics              |
| <b>Xylene</b>                       | Moderate; CNS effects, liver/kidney damage                            | Flammable; irritant  | VOC; harmful to aquatic organisms               | Cleaning, degreasing, solvent for resins and inks             | Printed circuits, microelectronic assemblies, PCBs   |
| <b>N-Methyl-2-pyrrolidone (NMP)</b> | Moderate to high; reproductive toxicity, skin absorption              | Flammable; irritant; harmful if inhaled                        | Persistent in water; toxic to aquatic organisms | Photoresist strippers, solder mask removal                    | Semiconductors, advanced ICs, LCD displays           |
| <b>Dimethylformamide (DMF)</b>      | High; liver toxicity, reproductive toxicity                           | Flammable; irritant; harmful by inhalation and skin absorption | VOC; toxic to aquatic organisms                 | Solvent for polymers, resins, photoresists                    | Flexible circuits, polymer coatings, display films   |
| <b>Methanol</b>                     | High; toxic by ingestion, inhalation, skin absorption; CNS depression | Flammable; irritant  | VOC; toxic to aquatic life                      | Cleaning, degreasing, thinner for inks/coatings               | Batteries, PCBs, sensors                             |
| <b>Ethyl Acetate</b>                | Low to moderate; CNS effects at high exposure                         | Highly flammable; irritant                                     | VOC; biodegradable                              | Cleaning, degreasing, solvent for coatings and adhesives      | Solder masks, electronic adhesives, display coatings |

| Solvent  | Toxicity   | Hazards                                     | Environmental Risks                    | Purpose / Application  | Example Products   |
|--|--|---|--|--|--|
| <b>Propylene Glycol Monomethyl Ether (PGME)</b>      | Low to moderate; irritation to eyes and respiratory system   | Flammable; mild irritant                    | VOC; biodegradable                     | Photoresist thinner, cleaning agent                              | Photolithography processes, IC fabrication, printed electronics        |
| <b>Trichloroethylene (TCE)</b>                       | High; carcinogenic, CNS depression, liver/kidney toxicity    | Non-flammable; toxic by inhalation and skin | Persistent; toxic to aquatic organisms | Degreasing metal parts, cleaning PCBs (restricted use today)     | High-precision connectors, metal housings, legacy electronics cleaning |
| <b>Perchloroethylene (PCE / Tetrachloroethylene)</b> | Moderate to high; liver/kidney toxicity, possible carcinogen | Non-flammable; irritant                     | Persistent; toxic to aquatic life      | Metal cleaning, solvent in dry cleaning of electronic components | Semiconductor equipment parts, metal chassis, legacy PCB cleaning      |

### Plastics used in electronics

| Plastic                                      | Typical Use in Electronics                             | Sustainability / Environmental Notes  |
|--|--|---|
| <b>PVC (Polyvinyl Chloride)</b>              | Cables, insulation, housings, flexible parts           | Difficult to recycle; can release harmful substances (dioxins, HCl) when incinerated; contains additives like plasticizers that may be toxic. |
| <b>ABS (Acrylonitrile Butadiene Styrene)</b> | Casings for computers, printers, TVs, keyboards        | Durable and recyclable in theory, but mixed-material products complicate recycling; not biodegradable; energy-intensive production.           |
| <b>PC (Polycarbonate)</b>                    | Optical discs, lenses, protective covers, LED housings | Can be recycled, but less common; potential BPA leaching; production is energy-intensive.   |
| <b>PS (Polystyrene)</b>                      | Packaging, insulation, some housings                   | Lightweight, cheap, but difficult to recycle in electronic applications; can persist in the environment; often incinerated.                   |
| <b>PP (Polypropylene)</b>                    | Internal components, battery casings, connectors       | Relatively easier to recycle; low toxicity; biodegradable only very slowly; lightweight, so energy savings in transport.                      |
| <b>PE (Polyethylene)</b>                     | Cable insulation, wire coatings, some housings         | Widely recyclable, low toxicity; very durable and persistent in environment if not recycled.  |
| <b>Nylon (Polyamide, PA)</b>                 | Gears, bearings, connectors, structural components     | Strong and durable, recycling is limited; production is energy-intensive; not biodegradable.  |

| <b>Plastic</b>                          | <b>Typical Use in Electronics</b>       | <b>Sustainability / Environmental Notes</b>   |
|---|---|---|
| <b>PET (Polyethylene Terephthalate)</b> | Insulating films, capacitor films, PCBs | Widely recyclable; durable; can accumulate in environment if not properly managed.                        |
| <b>PBT (Polybutylene Terephthalate)</b> | Connectors, switches, housings          | Limited recycling options; durable; long lifespan but persistent in environment.                          |
| <b>ABS/PC Blends</b>                    | Casings and structural components       | Same issues as ABS and PC; blending complicates recycling; long lifespan but energy-intensive to produce. |