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Circular Thermoregulating Textiles: Protecting Agricultural Workers from Extreme Heat

HeatShield Apparel Project

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The Problem

35X

Agricultural workers are 35 times more likely to die from heat exposure than those working in other sectors. (Gubernot, Anderson, & Hunting, 2015)

21 DAYS

The average agricultural worker faces 21 days a year in unsafe heat conditions.

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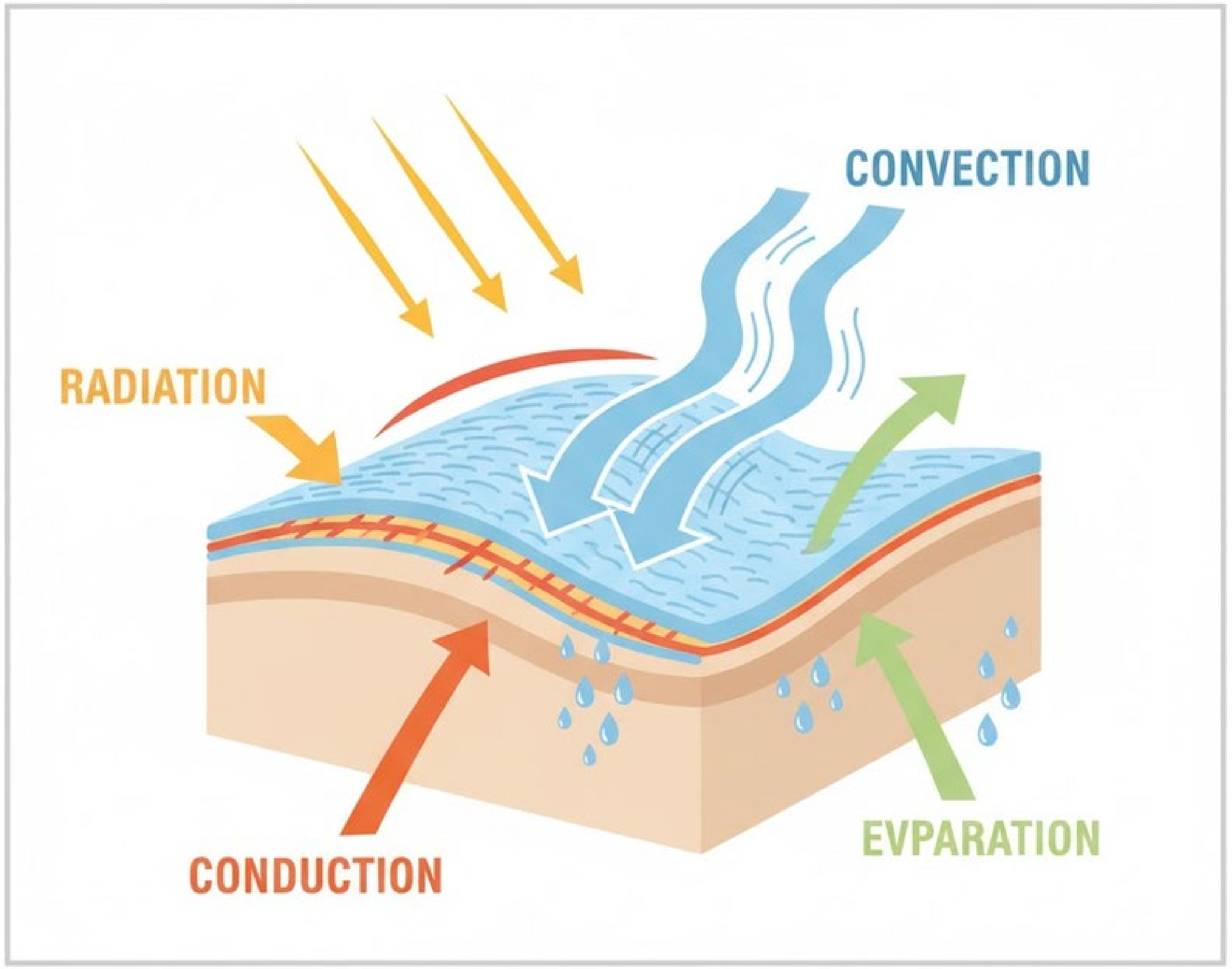
Dual Challenge

WORKER SAFETY

SUSTAINABILITY

Advanced protective materials + Circular design = Sustainable Worker Protection

Heat Transfer Fundamentals



Heat Transfer Method	Description	Textile Goal	Key Metrics
Radiation	Heat from an external source (e.g., sun, fire).	Reflect or block	UPF, Reflectivity, Emissivity
Conduction	Heat transfer through direct contact (fabric on skin).	Insulate or conduct away	Thermal Conductivity/Resistance
Convection	Heat carried away by moving air.	Allow air penetration or block wind	Air Permeability
Evaporation	The body's primary cooling system (sweat).	Pull moisture from skin & release vapor	Wicking Rate, Evaporative Resistance (Ret)

Advanced Cooling Textile Strategies

Protective textiles are engineered to manage heat stress.
We can categorize them into three primary groups:

- **Passive Cooling:** Using material science to enhance the body's natural cooling.
- **Responsive Textiles:** Smart fabrics that adapt to environmental changes.
- **Active Cooling:** Powered garments for maximum cooling in extreme condition

Conductive Textiles (Passive)

Employs materials with high thermal conductivity to act as a heat sink

- **Material Examples:**
    - Coatings: Carbon Nanotubes (CNTs) or graphene coated onto a base fabric
    - Composite Fibers: Boron-Nitride (BN) nanosheets are integrated directly into polymer fibers (e.g., a-BN/PVA) to create an inherently conductive textile
- **Key Challenge:** Conductive coatings can suffer from cracks or delamination during wearing and washing, while composite fibers are often more durable.

Radiative Textiles (Passive)

Manipulates a fabric's optical properties.

- Solar Reflective (Outdoor): Coated fabrics block incoming heat from solar radiation.
- Infrared Transparent (Indoor/Outdoor): Allows the body's own mid-infrared (mid-IR) radiation to pass directly through the fabric and escape.

Key Technology: Nanoporous Polyethylene (nanoPE) can simulate skin temperature by 2.0°C to 2.7°C compared to traditional cotton fabric (Farooq & Zhang, 2021; Sajjad et al., 2022).

Evaporative Cooling

Category 1: Membrane Laminates

- Three-layer fabrics that hold water in a central core.This water evaporates to actively cool the skin.
- **Pro:** Lightweight, flexible, and does not require soaking the entire garment.
- **Con:** Cooling performance drops significantly in high-humidity environments due to the low vapor pressure difference.

Evaporative Cooling

Category 2: Vacuum Desiccant Cooling (VDC)

- A portable system using cooling pads containing a desiccant (drying agent) and a water layer.
- A vacuum is pulled, forcing rapid evaporation from the water layer, which is then trapped by the desiccant.
- **Performance:** Provides powerful, active evaporative cooling with an estimated capacity of 373.1 W/m^2 (Sajjad et al., 2022).

Responsive Textiles (Adaptive)

The fabric's physical structure automatically changes in response to an external heat source.

Key Technology:

- Shape Memory Alloys (SMAs): Tiny metal springs (e.g., Nitinol) are embedded between the fabric's inner and outer layers.
  - At Normal Temp: The springs remain compressed or "flat."
  - At High Temp: When they reach a set "actuation temperature," the springs automatically expand, physically pushing the fabric layers apart.

Active Cooling

- **Micro-Fan Ventilation**
  - Battery-powered fans are integrated into a vest or jacket to circulate ambient air (Sajjad et al., 2022).
  - This enhances both convective cooling and sweat evaporation (Sajjad et al., 2022).
  - Limitation: Best for moderate heat. In extreme heat, it can blow hot air onto the worker (Sajjad et al., 2022).

Active Cooling

- **Liquid-Cooled Garments (LCGs)**
  - A battery-operated pump circulates chilled liquid (e.g., water) through a network of small tubes stitched into a vest (Sajjad et al., 2022).
  - This provides powerful, direct conductive cooling and is often considered the "gold standard" for extreme heat or sealed environments (Farooq & Zhang, 2021; Sajjad et al., 2022).

Active Cooling

- **Phase Change Materials (PCMs)**
  - Vests contain packs of materials (e.g., hydrated salts, paraffins) that melt at a specific, cool temperature (e.g., 21°C - 28°C) (Sajjad et al., 2022).

As the PCM melts, it absorbs a large amount of latent heat from the body, but the impermeable nature of PCM packs can block sweat removal.

The Future: Hybrid Cooling Systems

- Almost every cooling method has a limitation (e.g., PCMs trap sweat, fans are ineffective in extreme heat).

- Hybrid systems combine two or more techniques to create an optimized garment.

Example 1: PCM + Micro-Fans

- This is one of the most common hybrid systems.
- The PCMs provide the primary cooling, while the fans actively manage the sweat and moisture trapped by the impermeable PCM packs (Sajjad et al., 2022).
- A field study of 140 construction workers found 91% preferred this hybrid vest over no cooling (Chan et al., 2017)

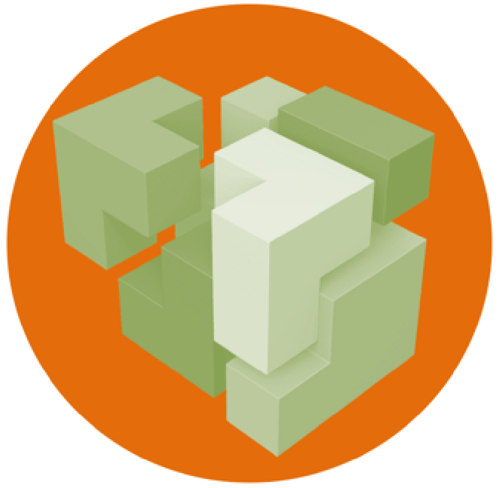
Example 2: PCM + Liquid Cooling (LCG)

- The PCM acts as a rechargeable "heat sink" for the liquid, improving the system's overall efficiency and extending its cooling duration
- One study found this hybrid provided a 26% improvement in cooling performance over an LCG system alone (Wang et al., 2015)

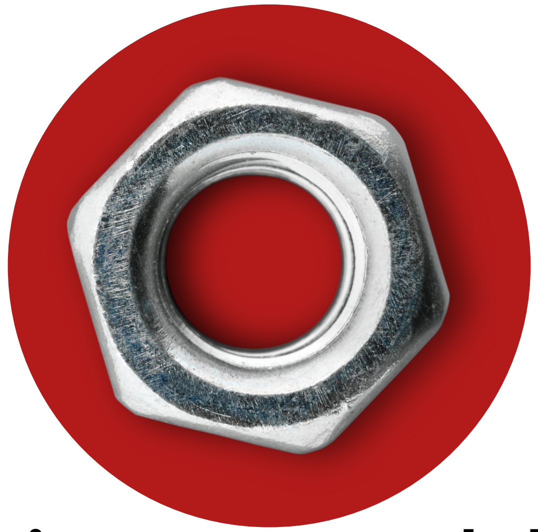
Circularity in Functional Apparel Design

Circular Design Principles

Longevity

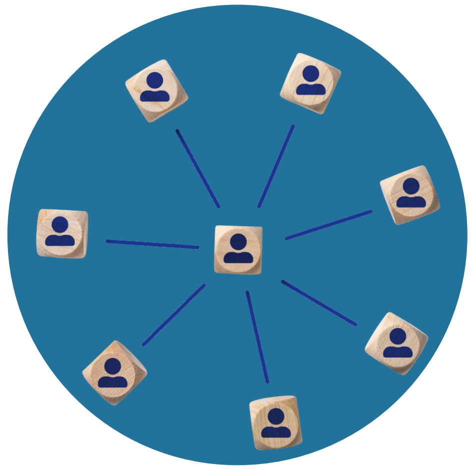


Modularity



Disassembly

Material Health



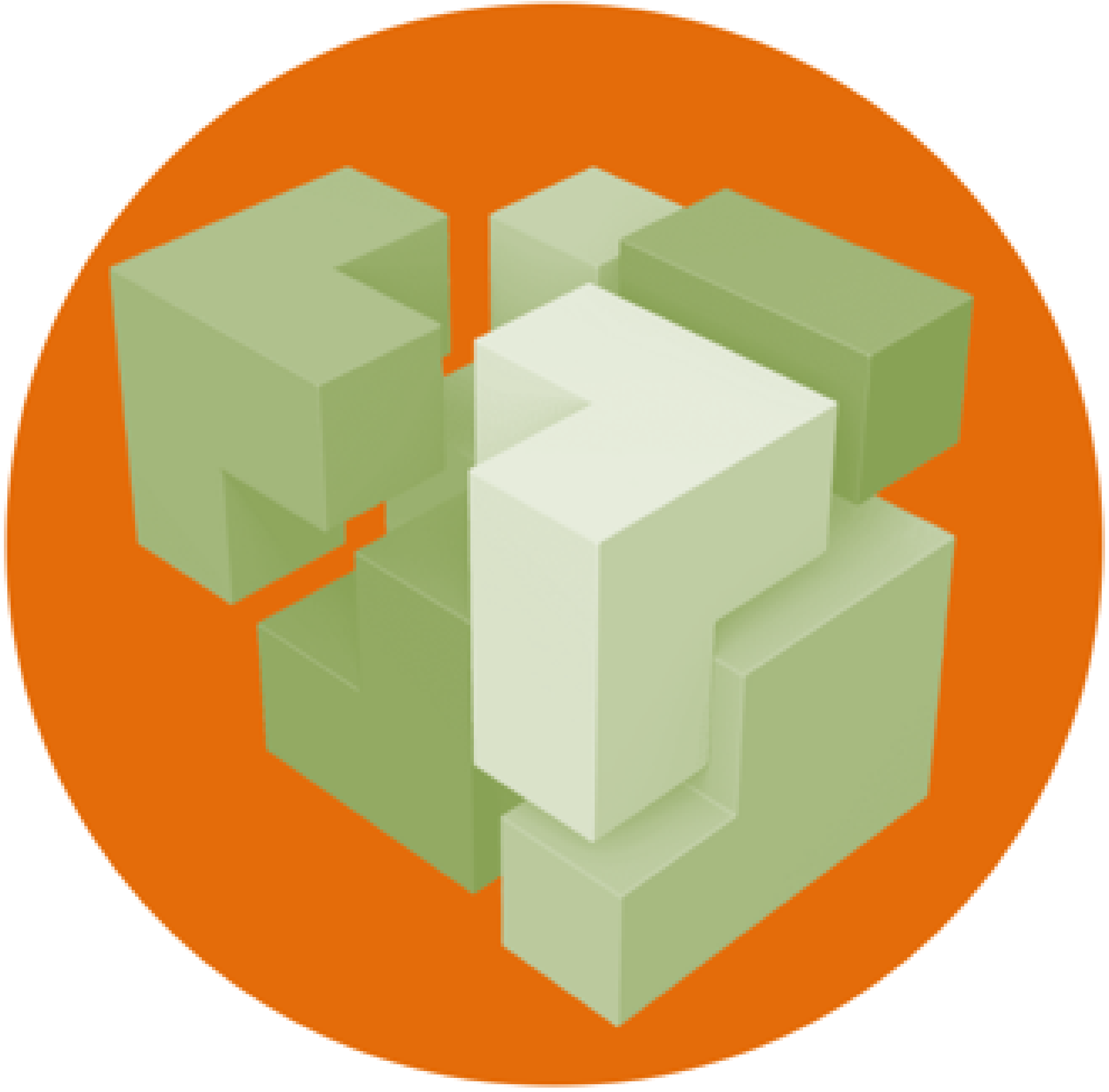
System Thinking

Design for Longevity

Design for longevity in the context of functional apparel refers to the intentional creation of garments with an optimal lifespan by focusing on durability, repairability, upgradability, and emotional attachment (Benkirane et al., 2022; Carlsson et al., 2021).

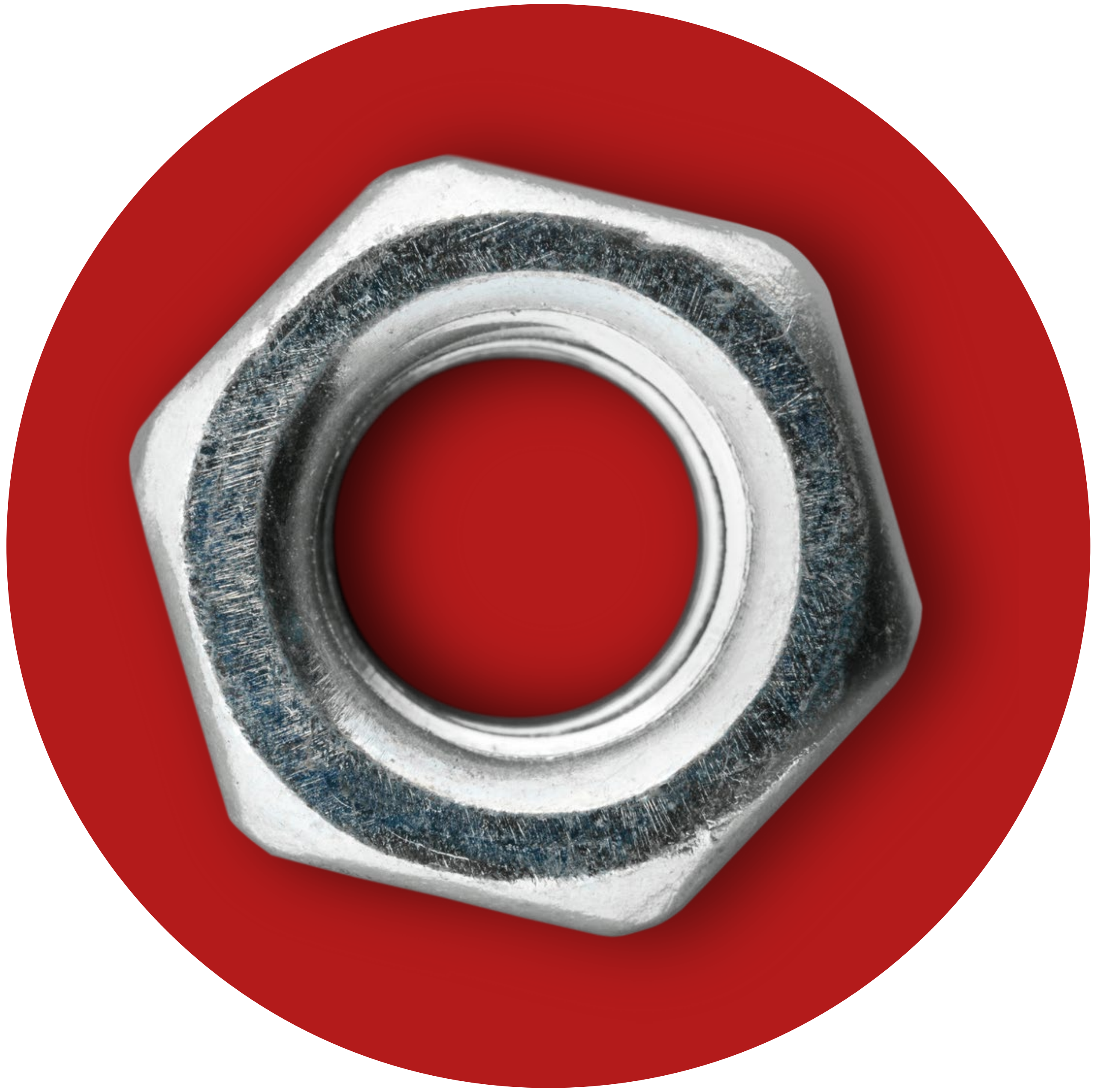
Design for Modularity

Design for modularity refers to creating garments that can be disassembled into multiple parts. These parts can be zipped, buttoned, or otherwise attached and detached, allowing users to reconfigure garments for different needs, environments, or preferences (Zhang et al., 2024; Chen & Lapolla, 2021).



Design for Disassembly

Designing for disassembly means a product's components can be easily, rapidly, and cost-effectively separated, then reused or recycled (Weetman, 2017)

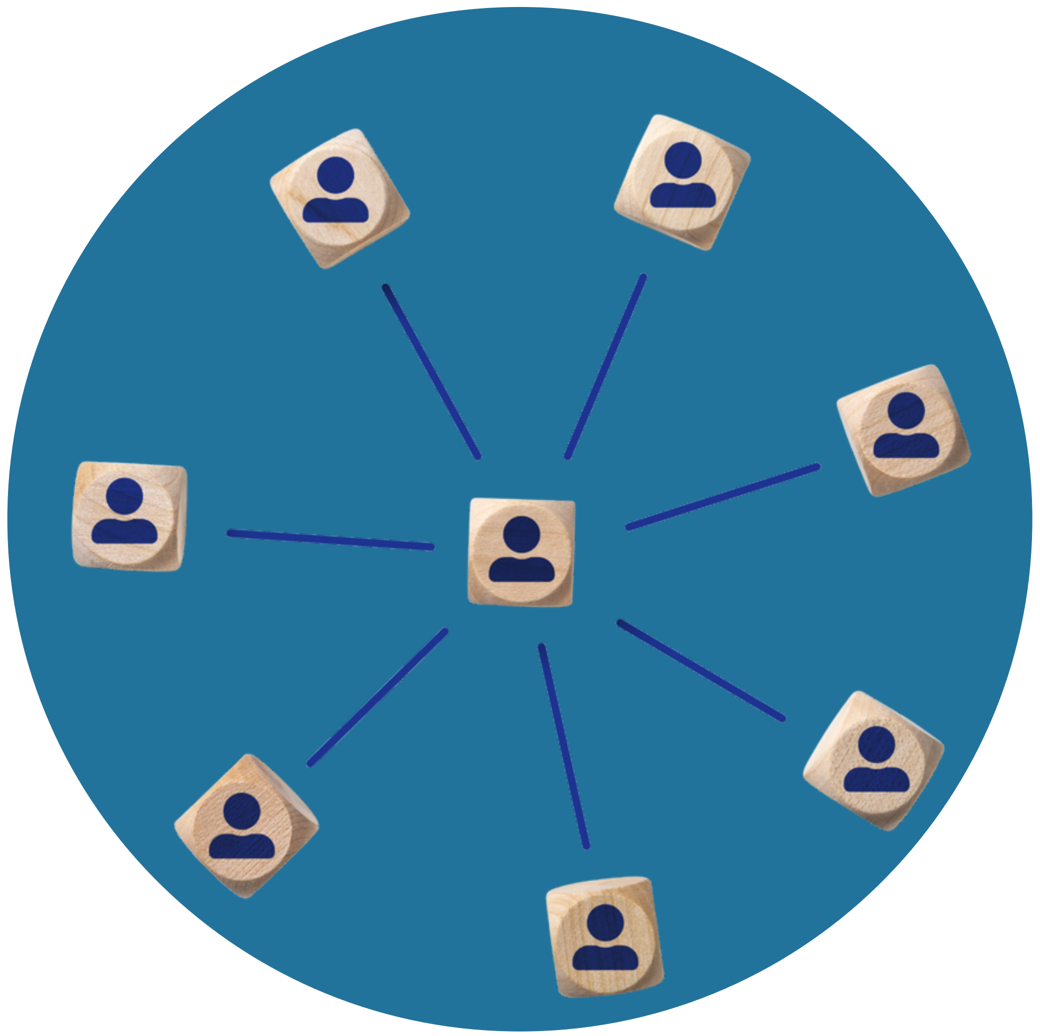


Design with Material Health

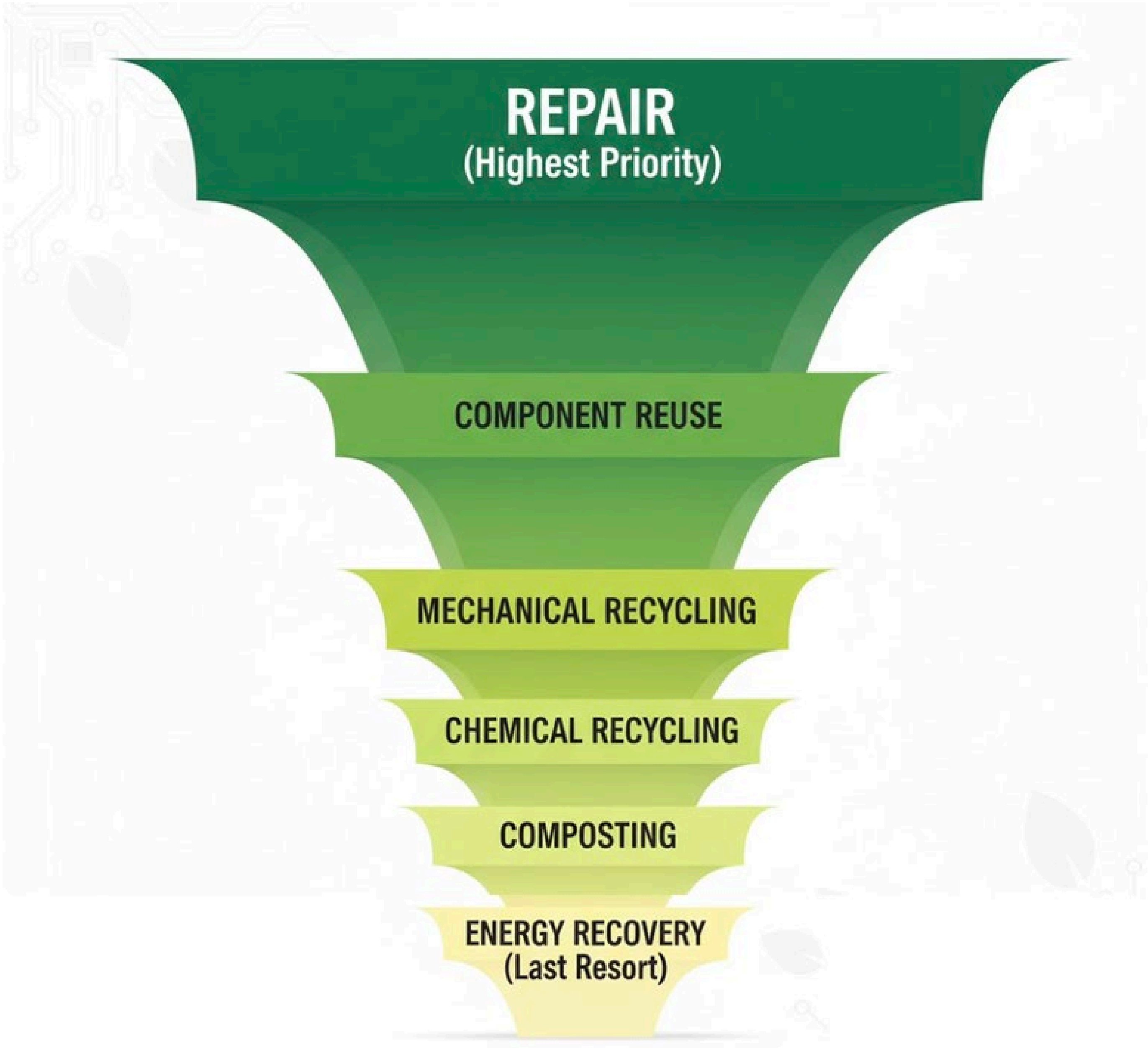
Design with material health for functional apparel is an integrated, design-led approach that selects non-toxic and high-performance materials while validating wearer safety and product functionality.

Design for System Thinking

Design for systems thinking in functional apparel involves creating clothing solutions by considering the interconnectedness of user needs, technical requirements, and broader social, technological, and environmental systems (da Costa Junior et al., 2019).



Next Life Pathways



Acknowledgements

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