The Development of an Encapsulated Bio-Based Phase Change Material for Cooling Garment Applications

Racquel Sherise Lallie, Emmanuel Kweinor Tetteh, Sudesh Rathilal, Philip Jaeger

***Abstract*— Heat stress is a growing concern in occupational settings and a public health issue that has motivated the development of cooling garments. This paper presents the development of an encapsulated bio-based phase change material (PCM) system intended for the integration into cooling clothes. Material selection, encapsulation technique, mass and energy balance considerations, process equipment selection and HAZOP analysis are thoroughly discussed. Capric acid, sourced from coconut oil, was selected as the PCM due to its melting range and biodegradable origin, and Polylactic acid (PLA) was chosen as the microcapsule shell material for its ease of integration into textiles. Microencapsulation and coating integration were identified as the ideal containment method to ensure resistance to leakage and comfort to the wearer. The process design included unit operations for the extraction and preparation of capric acid and polylactic acid, as well as encapsulation and coating, along with equipment specifications and energy considerations for design-scale-up. Through the HAZOP analysis, solvent handling and thermal/pressure control were highlighted as critical controls. The proposed product concept targets a vest containing 300 grams of encapsulated PCM and represents a sustainable alternative to paraffin–based PCM for cooling garment applications. Key recommendations include strict process control, inline quality checks and end-of-life management to ensure environmental performance and user safety.**

***Keywords*— Cooling Garments, Microencapsulation, Phase Change Material, Process Design**

I. INTRODUCTION

Rising ambient temperature and increased exposure to heat stress drive a need for low-energy, wearable cooling solutions that are suitable for work and leisure environments [2-6]. Phase change materials (PCMs) provide thermal comfort by absorbing latent heat during melting and releasing it during solidification,

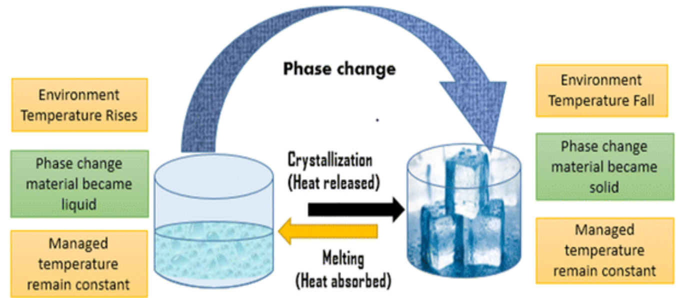

Fig. 1 : Operational principle of Phase change materials (PCMs) [1]

making them attractive for garment integration to create microclimates that reduce physiological strain. The principle behind this is represented in Figure 1. Historically, paraffin-based PCMs have dominated textile applications, but bio-based alternatives are desirable to reduce environmental impacts and improve biodegradability. [7-9].

Bio-based PCMs offer an eco-friendly route towards PCM applications because they are renewable resources. These types of materials are usually fatty acids or alcohols, as displayed in Fig. 2. Whilst PCMs are an attractive field for numerous applications, including temperature manipulation, data storage, construction, bio-based materials are gaining more attention for thermal energy storage applications, as highlighted in studies by Yadav, et al. [10]. Another review by Benhorma, et al. [11] explained that bio-based PCMs have high energy potential and are easily scalable. Sharma, et al. [12] reported that PCMs derived from biological material, such as waste, can also provide waste remediation while offering the benefits of thermal energy storage.

This work presents the chemical product development and process design for an encapsulated bio-based PCM intended for the use in cooling vests with the goals of (1) selecting suitable bio-based PCM and encapsulation materials, (2) defining manufacturing unit operations and mass/energy balances for lab and industrial scales, (3) detailing equipment selection and (4) performing a safety (HAZOP) evaluation to inform safe scale up and manufacturing. In alignment with the United Nations Sustainable Development Goals 3, 9, and 13, which focus on

Racquel Sherise Lallie* is part of Green Engineering Research Group, Department of Chemical Engineering, Faculty of Engineering and the built environment, Durban University of Technology, Durban, 4001, South Africa.
Emmanuel Kweinor Tetteh
Sudesh Rathilal:
Philip Jaeger[2] is part of the institute of subsurface energy systems, Agricolastraße 10 ,Building C 21, Room 323 ,38678 Clausthal-Zellerfeld, Germany

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the health and well-being of people, innovation and infrastructure, and action against climate change, it is essential to use an eco-friendly, sustainable method to mitigate heat stress. This will also create or boost the market for an innovative product, creating employment opportunities and increasing economic status [13-15].

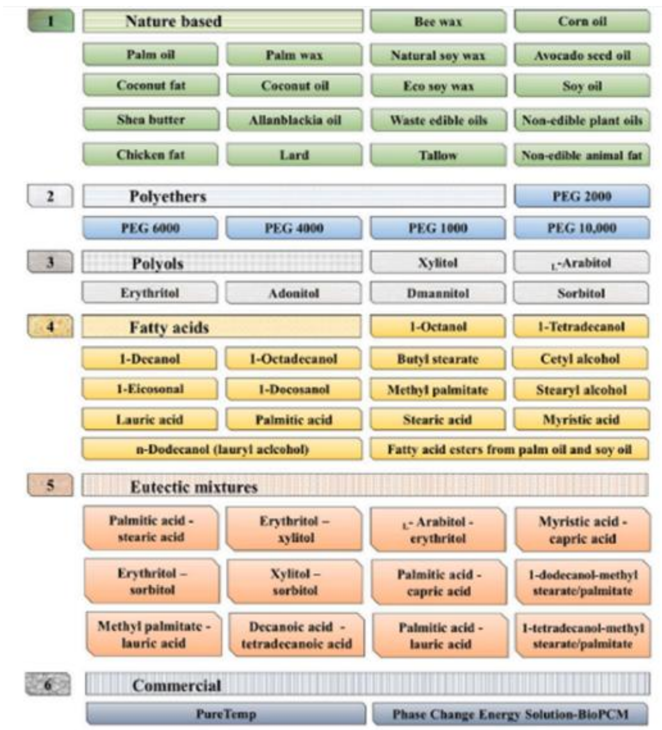

Fig. 2 : Classification of various bio-based PCMs with examples adapted from Benhorma, et al. [11]

II. MATERIAL SELECTION RATIONALE

A. *PCM selection*

Bio-based PCMs were screened against criteria including a suitable melting point for human cooling, non-toxicity, a safe environmental profile, life-cycle durability against thermal cycles, and availability as listed in Table 1. Capric acid (a fatty acid obtained from coconut oil) was identified as the most viable option because it meets the melting-point requirements for body-cooling applications, is bio-derived, and is more environmentally preferable than fossil-paraffin alternatives [10-12].

B. *Encapsulation material*

Containment of PCMs for garments requires robust shells that prevent leakage, enable mechanical durability in textiles and are chemically compatible with PCM and textile enablers as mentioned in Table 2. Polylactic acid was selected as the encapsulation material shell due to its biodegradability and compatibility with capric acid, and microencapsulation was chosen as the preferred containment technique to maximise integration with fabrics while ensuring user safety and comfort [16-18].

TABLE I : CRITERION USED FOR PCM SELECTION FOR COOLING GARMENT APPLICATIONS

Criteria	Importance in cooling garments
Thermal energy storage (TES)	Thermal energy storage applications require a high capacity to absorb high amounts of energy when needed.
Weight	The PCM must be light yet practical to avoid discomfort in textile applications.
Biocompatibility	Not harmful to the environment and must be biodegradable
Latent heat capacity	Efficient energy storage and release are essential for maintaining a cooling effect.
Thermal conductivity	The thermal conductivity must be sufficiently high to enable effective heat exchange.
Melting point	Must have an appropriate cooling range
Integration capability	Integration into textiles must be doable and straightforward.
Toxicity	Less toxic so as not to harm the wearer in case of leakage, as well as being eco-friendly
Life cycle	The PCM's life cycle must be able to withstand multiple thermal cycles.

TABLE II : CRITERION USED FOR ENCAPSULATION MATERIAL SELECTION

Criteria	Reasoning
Thermal possibility	The material should have a thermal capacity but not too much to overpower the PCM
Encapsulation efficiency	The formation of a shell around PCM is necessary for protection.
Chemical compatibility	The encapsulation material must be compatible with the PCM material but not reactive.
Biocompatibility	Sustainable and easy access, the material should also be biodegradable.
Ease of integration into fabric	Textile integration is essential; it must be comfortably integrated into fabrics.
Mechanical strength	Strength is required to prevent leakage.

III. PROCESS DESIGN AND UNIT OPERATIONS

The product development process was defined from feedstock extraction through final garment assembly, with unit operations adapted for both lab-scale and industrial-scale production which is summarized in the diagram in Figure 3. Key stages include raw material extraction and purification of capric acid, PLA preparation, microencapsulation, microcapsule conditioning and textile integration via coating and embedding.

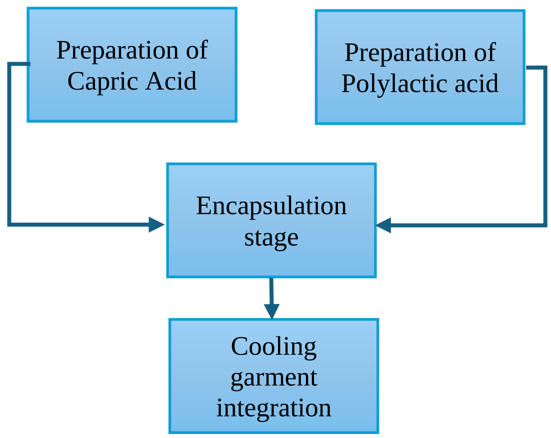

Fig. 3: Process stages for encapsulated PCM development

A. Capric acid and purification

Fatty feedstock separation can be achieved using distillation techniques tailored for triglyceride fractionation and fatty acid recovery. Simulated and short-path vacuum distillation arrangements were evaluated for separation performance and energy demand. A vacuum short path distillation unit with falling film configuration, multistage vacuum pumps, multistage condensing at low temperatures and throughput and purity specifications was recommended for industrial purification to achieve high purity capric acid suitable for PCM use [19-21].

B. Microencapsulation approach

Microencapsulation methods compatible with PLA shells and capric acid cores were considered, focusing on solutions that yield robust shells and high encapsulation efficiency. Physical containment, microencapsulation, and coating processes were prioritized for simplicity and reliable integration into textiles [22, 23].

C. Mass and energy considerations

Comprehensive mass and energy balances were prepared to size lab and industrial equipment, and to evaluate process energetics for extraction, distillation, encapsulation, and textile processing steps. The main findings are tabulated and summarised in Table 3 and Table 4. These balances informed the selection of equipment and operational parameters presented in specification sheets for both laboratory and industrial scales. The output and input are considered, as are the mass generated, and any losses incurred. The significance includes process design, safety compliance, environmental assessment, and resource conservation. The general mass balance equation follows the equation stated below:

$$Accumulation = Output - Input + Generation - Consumption \ldots\ldots (1)$$

TABLE III: SUMMARY OF MASS BALANCE RESULTS FOR RAW MATERIAL EXTRACTION AND PREPARATION PROCESS

Component	Input mass (g)	Output mass (g)	Loss
Capric acid	792	750	42 grams of loss during the process
Polylactic acid	264	250	14 grams of loss during the process
Solvent	2403	0	Solvent is used to completion
Total	3459	1000	Overall loss of 1067 grams

It is necessary to understand the flow of energy, safety regulations, and energy requirements that influence economic factors. The uses are integrated with mass balances to ensure safety, regulatory compliance, and process design and optimisation, as well as environmental impact. The general energy balance is formulated in equation 2.

$$Energy\ in - Energy\ out + Generation - Consumption = Energy\ Accumulated \ldots\ldots (2)$$

TABLE IV : SUMMARY OF ENERGY BALANCE RESULTS FOR EACH PROCESS STAGE

Step	Input	Output	Energy input
Preparation of capric acid	792 grams	750 grams	133640 Joules
Preparation of polylactic acid	264 grams	250 grams	9000 Joules
Encapsulation	3459 grams	1000 grams	919911 Joules
Garment Assembly	300 grams	300 grams PCM + garment mass	Negligible

The calculations show that the encapsulation step will consume the most energy. While ideal assumptions were made for the mass balance, there is also the possibility of losses that may reduce the weight or inconsistent removal and treatment that may increase the weight. The end goal is for the capsules to weigh 300 grams, achieving adequate cooling while maintaining a suitable weight for the garment. Considering that the applications will involve mostly outdoor activities, this is a reasonable weight to produce.

D. Equipment selection

Equipment selections were made for each unit operation, specifying options for both lab-scale and industrial-scale applications. These options included distillation units, reactors/homogenisers for encapsulation, filtration and drying, as well as coating equipment for textile integration. The selection was influenced by decision variables, including process requirements, sizing, and economic factors, as shown in Figure 4. The mass and energy balance provides the basis for determining the equipment to be used in the process. This section outlines the equipment required to produce encapsulated bio-based PCM from start to finish. The first part is for lab-scale production and testing, and the second part then presents industrial equipment. There are many options for equipment selection, but each piece of equipment is provided with a rationale for its selection. The process is divided into stages, with the materials needed listed and illustrated with descriptive pictures and diagrams.

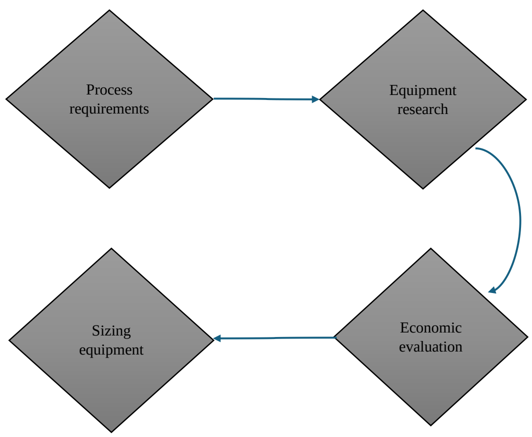

Fig. 4 : Decision factors for equipment selection [18]

A. *Lab – scale equipment required*

Stage 1 - material preparation

- Precision balance – needed to weigh the materials accurately
- Hotplate and magnetic stirrer – required for the melting of the capric acid and the dissolving of the PLA, which is done separately, but can be used for both
- Ultrasonic cleaner – used to degas the PLA solution and prevent any voids from forming during the encapsulation process

Stage 2 - microencapsulation process

- High shear homogeniser - used to stabilise and create an oil-in-water emulsion using capric acid as the dispersed phase
- Magnetic stirrer – required for the maintenance of the emulsion during the solvent evaporation process
- Rotary evaporator – used for the removal of solvent in low-pressure conditions
- Vacuum pump – used in combination with the rotary evaporator
- Water bath – needed for the maintenance of a constant temperature during evaporation

Stage 3 - encapsulation and stabilisation

After the PLA and Capric acid have formed the core and shell structures, washing and drying are required before collecting the capsules. The required equipment is listed below :

- Centrifuge – needed to separate the solid capsules from the aqueous phase
- Vacuum oven – used for gentle drying of the capsules and will avoid phase change during the drying process
- Buchner funnel – for further separation of the liquid and the solid to ensure there is no moisture in the capsules

Stage 4 - Quality check and characterization

The microcapsules need to be inspected and characterised before they are integrated into the fabric. The following devices can be used for quality checks:

- Differential scanning calorimeter – used to test the phase change temperature and latent heat
- Thermogravimetric analyser – needed to test thermal stability and the degradation profile
- Scanning electron microscope – used to check the structure and morphology of the capsules in case there is a need for optimisation
- Fourier transform infrared spectrometer – used to confirm chemical integrity and interaction

Stage 5 - integration into the fabric

- Pad dry cure machine – used to apply the capsules to fabric using binders
- Binder mixer – used for the coating formulation
- Tensile tester – can test the tension and strength after treatment
- Thermal manikin or an infrared camera – used to evaluate the cooling performance

B. *Proposed Industrial-scale equipment*

Stage 1 – Raw material preparation

- Splitter column operating between 105-145 0C with a flow rate of 150-220 kg/h
- Hydrolysis reactor operating at 0,85 MPa with a catalyst injection system
- Vacuum distillation system, which consists of a short path distillation unit operating at 740 mmHg vacuum, and a temperature-controlled receiver, which is about 160 0C, used for capric acid and a falling film evaporator

Stage 2 – Processing of the polylactic acid (PLAneo technology)

- Twin screw extruder operating at a ratio L/D of 40:1 with temperature zones ranging from 160-220 0C
- Rotary vacuum dryer operating at 800C temperature to dry the pellets, performed in 10 hours
- High-speed mixer with a 1000 L capacity and a heating jacket

Stage 3 – Microencapsulation

- High-pressure homogeniser operating at 10000-20000 rpm and between 50-100 MPa, it is used to create the oil and water emulsion between the capric acid and PLA
- Temperature-controlled reactor with a jacketed glass vessel, an anchor impeller, and a solvent recovery condenser at -20°C chilling temperature

- Membrane filtration system used for the separation of the microcapsules from the aqueous phase
- Differential scanning calorimeter used for the phase change optimization by testing the enthalpy, the target is 150-205 J/g
- Laser diffraction particle analyser, which is to be used for the monitoring of particle size in a range of 1-500 micrometres

Stage 4 – Textile integration using coating

- Padding mangle, which is a 3-bowl system, with a temperature range of 80-120 0C for the drying zones and a capacity of 20-50 m/min fabric speed
- Ultrasonic spray coater used for precision application and operated at a temperature of 29°C with a pneumatic atomising system

Stage 5 – manufacturing of the garments

- Computerised cutting table for laser-guided pattern nesting to design the vest
- Industrial cover stitch machines are used for seam sealing for the PCM to maintain compartment integrity

Stage 6 – Quality control

- Accelerated thermal cycling chamber operating at a range of -10-50 0C with a 5000-cycle capability
- Thermogravimetric analyser, which will be used to test the efficiency of the capsules. The goal is to get it to 95% efficiency minimum
- Martindale abrasion tester used to test the durability of the garment under a pressure of 12 kPa

IV. GARMENT INTEGRATION AND PRODUCT SPECIFICATION

Integration routes evaluated included surface coating with binders and embedding microcapsules into fibres during textile manufacturing, with the coating method selected for vest assembly to minimise fabrication cost and complexity. A representative product specification envisions a prefabricated vest into which approximately 300 grams of encapsulated PCM is incorporated via a coating process, balancing cooling capacity and ergonomics [24]. The proposed specifications of the final product are listed in Table 5 and Table 6.

TABLE V : PROPOSED PRODUCT SPECIFICATIONS

Parameter	Specification
Product name	PCM cooling vest
Material of the vest	100% cotton
PCM type	Capric acid (C10)
PCM loading	300 grams per vest
PCM distribution	4-8 removal pouches
Microcapsule size	1-10 hm
Encapsulation efficiency	80-90%
Vest size	Unisex for a typical adult
Closure system	Front zipper with Velcro waist and shoulder straps adjustable
Weight of product with PCM	1-1,5 kg
Color	Customizable
Washability	Machine wash

Table 1 : Expected thermal performance of final product

Thermal performance	
Parameter	Specification
Phase change temperature	29-31 ^{0}C
Latent heat of fusion	79-150 J/g
Cooling duration	2-4 hours
Cooling capacity per vest	23,7-45 kWh
Recharge time	30-60 minutes in a freezer
Thermal conductivity	0,15-0,31 W/mK
Thermal stability	500 freezing
Vest size	Unisex for a typical adult
Closure system	Front zipper with Velcro waist and shoulder straps adjustable
Weight of product with PCM	1-1,5 kg
Colour	Customizable
Washability	Machine wash

V. SAFETY, QUALITY AND HAZOP RECOMMENDATIONS

A HAZOP analysis identified critical process hazards and mitigation measures across solvent handling, thermal control, pressure management, product quality, and human factors. Key recommendations include the use of explosion-proof equipment and solvent containment for solvent-based steps, redundant temperature controls and calibration to prevent polymer or PCM decomposition, pressure relief devices for reactors and homogenisers, inline and final product quality control to prevent leakage or off-spec products, and operator training. Environmental and waste-handling controls – ventilation, solvent recovery, and safe disposal - were also emphasised to minimise emissions and occupational exposure.

Solvent Exposure

- Install infrared (IR) sensors for DCM leak detection (action threshold: 25 ppm)
- Implement closed-loop solvent recovery (≥95% efficiency)

Combustible Dust

- Use PLA pellets with anti-static additives (resistivity $<10^{9}$ Ω·cm)
- Class II Division 2 Hazardous Area Classification in processing zones

High-Temperature Risks

- Redundant thermal cutoffs on distillation columns (140°C max)
- Steam-inerted screw extruders for PLA processing

Waste Management

- On-site neutralization of alkaline wastewater (pH 6-9 discharge)

- Pyrolysis unit for non-recoverable PLA waste (energy recovery)

Regulatory Compliance

- **OSHA:** Process Safety Management for DCM handling
- **EPA:** leaks monitoring and reporting for DCM
- **REACH:** Registration required for capric acid
- **Biodegradability:** Verification for PLA components

Recommendations:

- Pilot-scale testing to validate 95% solvent recovery rates
- Explore CO_2 -based microencapsulation to eliminate DCM
- Negotiate long-term sugarcane PLA contracts to hedge price volatility

Bio-based phase change materials offer a sustainable and Discussion

A. Performance and sustainability implications

Switching from paraffin to bio-based PCM, such as capric acid, supports reduced reliance on fossil feedstocks. It offers potential end-of-life improvements due to the biodegradability of PLA shell, provided disposal is managed responsibly. Microencapsulation facilitates safe user contact and enhances durability and laundering resilience when properly engineered and quality controlled.

B. Manufacturing feasibility and scale-up

The defined mass and energy balances, along with equipment specifications, demonstrate a technically feasible scale-up pathway from laboratory to industrial production. Critical success factors include controlled purification to obtain high purity capric acid, reproducible encapsulation yields, and reliable integration of coating to ensure consistent thermal performance and durability. Energy and capital intensity are concentrated in purification and encapsulation stages, which merits optimization for economical scale manufacture.

C. Hazard assessment and economic analysis

For each process stage, the hazardous chemicals were identified and are displayed in Table 7 and Table 8. A feasibility study was conducted to determine the profitability of the final product. The main findings are presented in Table 9, followed by a discussion of the tables mentioned above.

TABLE VII: HAZARDOUS CHEMICALS AND ANALYSIS

Material	**Risk Profile**	**Emission Sources**	**Control Measures**
Dichloromethane	Carcinogen, Volatile organic compounds (≤300 ppm TWA)	Microencapsulation reactor vents	95% solvent recovery, scrubbers
Capric Acid	Irritant (skin/eyes), combustible	Distillation leaks, spillage	Double-walled tanks, PPE
PLA Dust	Respiratory irritant (PM10)	Pelletizing, textile coating	High efficiency air purification filtration, localized exhaust
KOH/NaOH	Corrosive (pH 12-14)	Transesterification, hydrolysis	Neutralization tanks, sealed systems

The most severe health hazard is Dichloromethane (DCM) due to its carcinogenicity and volatility; therefore, the proposed 95% recovery system and gas scrubbing are essential to maintain airborne concentrations below the 300 ppm TWA limit. The capric handling requires secondary containment and personal protective wear because of possible skin irritations or fire hazards. Dust generation from PLA is a typical issue in polymer processing; filters and adequate ventilation are needed to minimise exposure to workers. Overall, these control measures focus primarily on source containment, ventilation, and personal protection, addressing both acute and chronic risks.

Emissions Inventory: *System Boundary: Cradle-to-gate (raw materials to finished vest)*

TABLE VIII: CARBON EMISSION ANALYSIS

Component	**kg CO_2**	**Notes**
Capric Acid (C10)	0.78	Includes coconut farming (0.32 kg), purification (0.46 kg)
PLA Shell	0.15	Biogenic: -0.55 kg, Fossil: +0.70 kg
Microencapsulation	1.02	Solvent production (0.81 kg), energy (0.21 kg)
Textile & Manufacturing	0.45	Cotton farming, coating energy
Total per Vest	**2.40**	37% from fossil sources

As listed in Table 8, the energy-related carbon dioxide emissions from capric acid purification are modest (120 kg/t). They can be offset by recovering waste heat, which also reduces the plant's overall energy demand. Cyclohexane VOCs are the only non-CO_2 organic emissions that require temperature control on the condenser to limit the atmospheric release of the vapours. The production of PLA dominates the carbon balance but is classified biogenic because the polymer originates from a naturally occurring resource, coconut; therefore, the carbon dioxide is part of the short-term carbon cycle and does not require capture. An extended vacuum-stripping stage controls the residuals of the DCM in the micro-encapsulation step, achieving less than 300 ppm in the final product. This meets the occupational exposure limits and prevents product contamination. Particulate matter formed during the coating process can be addressed with a wet electrostatic precipitator, which ensures the efficient removal of fine dust. The mitigation actions are process-specific and aim to either capture the pollutants or reuse waste energy. The effectiveness hinges on proper design and operational control.

TABLE IX: ECONOMIC ASSESSMENT

Metric	**Value**	**Analysis**
Breakeven Price	\$19.80/vest	At 85% capacity utilization
ROI Period	4.2 years	Based on \$25/vest wholesale price
Sensitivity Drivers	Solvent recovery	10% efficiency gain → \$0.35 cost reduction

The breakeven price indicates the financial viability under the assumption that the plant operates at a capacity of 85%. The return on investment suggests that the cash inflow will balance the cash outflow in under 5 years, which is relatively short compared to most capital-intensive products, thereby presenting a strong financial case. Solvent recovery has been identified as the most influential cost lever; however, a mere 10% improvement in this area can significantly increase the profit margin.

D. Limitations and further work

Remaining uncertainties include long-term cycling behaviour and mechanical durability of the PLA microcapsules under real-world garment use and laundering, the detailed thermal performance of the vest in varying climates and activity levels, and end-of-life pathways for composite textiles containing encapsulated PCMs. Future work should include accelerated thermal-cycling tests and wear-and-laundering studies.

VII. CONCLUSION

This work presents a complete product development pathway for an encapsulated, bio-based PCM cooling vest using capric acid cores and PLA microcapsule shells, including rationale for material selection and process flows. Mass and energy balance considerations, equipment specifications, garment integration strategies and HAZOP-driven safety/control framework for scale-up. The proposed design provides a sustainable alternative to paraffin-based PCMs for personal cooling; however, field testing, durability assessment and lifecycle management are required before commercialisation.

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