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(57) Abstract:

The present invention discloses a modular, passive wildfire mitigation system termed Smart Pyro-Resistant Forest Zones, designed to protect forest-adjacent communities, infrastructure, and ecologically sensitive landscapes. The invention integrates two synergistic components: a top-layer mulch mat embedded with phase change materials (PCMs) and a sub-layer biochar buffer trench. The mulch mat is fabricated from palm frond fibers infused with a eutectic PCM blend (palm stearin-lauric acid) and encapsulated within thermally stable silica aerogel microspheres. When exposed to elevated temperatures between 45°C and 60°C, the PCMs absorb radiant heat, undergoing a solid-liquid transition that passively delays surface ignition. Beneath this thermal-absorptive layer lies a trench of granular biochar derived from pyrolyzed pinewood, which acts as a non-combustible flame barrier, reducing lateral fire spread and enhancing soil carbon content post-exposure. Anchoring is achieved using biodegradable bamboo stakes, enabling low-tech or drone-based deployment in fire-prone terrains. The dual-action system demonstrates significant delay in ignition and lateral flame propagation, requiring no external energy input and degrading fully within one year. The invention is environmentally restorative, cost-effective, and scalable, offering a breakthrough in sustainable fire management strategies under the growing threat of climate-induced wildfires.

FORM - 2

THE PATENTS ACT, 1970

(39 OF 1970)

&

THE PATENTS RULES, 2003

COMPLETE SPECIFICATION

(see Section 10 & rule 13)

**Integrated PCM-Based Thermal Absorptive Mulch and Biochar Trench
System for Forest Fire Resistance**

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3. PREAMBLE TO THE DESCRIPTION:

The following specification particularly describes the invention and the manner in which it is to be performed.

FIELD OF THE INVENTION

The present invention relates to wildfire prevention and landscape fire mitigation systems. More specifically, it pertains to the development and deployment of Smart Pyro-Resistant Forest Zones that utilize thermally-activated phase change material (PCM)-infused mulch and biochar-based soil buffer systems to control and inhibit wildfire spread in forested, peri-urban, and wildland–urban interface (WUI) zones. The invention introduces a passive, scalable, and eco-engineered solution that delays ignition, reduces flame front velocity, and thermally insulates vulnerable areas using biodegradable materials, integrated thermal response properties, and natural carbon sinks.

The system is particularly effective in wildfire-prone regions where traditional firebreaks and suppression methods are reactive, labour-intensive, or environmentally harmful. This invention provides a sustainable, adaptive, and modular wildfire defence mechanism that can be deployed pre-emptively as a physical and thermally active fire barrier, reducing infrastructure losses, ecological degradation, and human endangerment.

BACKGROUND AND PRIOR ART OF THE INVENTION

2.1 Background of the Invention

Wildfires have become more frequent, intense, and unpredictable due to climate change, drought, and land-use changes. Conventional wildfire control strategies primarily rely on reactive firefighting efforts, mechanical clearing, and fixed firebreaks using mineral soil or controlled burns. These methods are either unsustainable, ecologically damaging, or ineffective against fast-moving flame fronts.

A major challenge in wildfire control is the lack of pre-ignition passive systems that can dynamically absorb heat, delay combustion, and interrupt fire propagation across the landscape. Materials capable of thermal buffering—such as PCMs—have seen extensive application in construction and energy systems but remain underutilized in forest fire mitigation.

Biochar, a carbon-rich material derived from pyrolyzed biomass, is widely recognized for its ability to improve soil fertility and sequester carbon. However, its high thermal stability, moisture retention, and non-combustible nature also make it an ideal candidate for fire-resistant soil treatment in perimeter zones, especially if deployed in targeted patterns.

This invention addresses the absence of such combined thermally engineered and biodegradable solutions in the field of wildfire mitigation.

2.2 Limitations of Conventional Fire Mitigation Methods

1. **Non-Responsive Firebreaks:** Traditional mineral soil fire lines do not absorb heat or delay ignition—they merely create open spaces.
2. **No Thermal Absorption Function:** Current firebreaks and mulch systems do not incorporate latent heat absorption via phase change.
3. **Ecological Disruption:** Mechanical clearing often damages local vegetation and wildlife, leading to erosion and ecosystem imbalance.
4. **Lack of Biodegradability or Soil Enrichment:** Many synthetic fire retardants pollute the soil and require cleanup.
5. **Single-Layer Barriers:** Existing systems do not provide multi-layered protection combining thermal insulation and heat buffering.

2.3 Review of Prior Art

A. US Publication US20080214696A1 / US7666923B2 – “*Compositions and methods for resisting soil erosion and fire retardation*”

This invention describes an aqueous mixture of organic mulch and polyacrylamide copolymer applied hydraulically to land to reduce both soil erosion and fire spread. While it can retard surface fires when applied to vegetation or slopes, it uses conventional polymer mulch—it does **not incorporate phase change materials (PCMs)**, nor **biochar-based trenches** or dual-layer thermal buffering systems.

B. US Patent US7247263B2 – “*Fire-barrier composition (Acti-Quench)*”

Describes a sprayable gel composed of attapulgite clay and magnesium sulfate that increases water retention and slows fire spread when applied to vegetation or structures. This coating enhances evaporative cooling but does **not provide latent heat absorption**, biodegradable PCM mulch, or integrated soil biochar barriers.

C. Landscape and Biochar Application Research

Straw-biochar mulches applied after wildfires significantly reduce soil erosion (by 65–76%) in field trials, without influencing flame front delay or ignition resistance. These systems enhance soil regeneration but lack passive heat-absorbing action or structured firebreak design.

Reviews of biochar-to-soil amendments demonstrate benefits for soil health, carbon sequestration, and moisture retention. However, none of the studies propose biochar trenches as thermal-insulating firebreaks with ignition deterrent properties

2.4 Identified Gaps in Prior Art

- **No Passive Heat Absorption Mechanism:** Existing barriers do not employ PCM for phase-change thermal buffering.
- **No Dual-Layer Fire Mitigation Design:** Lack of combined top-layer (PCM mulch) and sub-layer (biochar trench) systems.
- **Limited Field-Deployable Configurations:** Prior solutions are either fixed, infrastructure-based, or chemically intensive.
- **Lack of Soil-Positive Environmental Impact:** Most retardants degrade ecosystems instead of enriching soil.

2.5 Need for the Present Invention

To address these critical shortcomings, the invention introduces a **smart, passive, and ecologically beneficial wildfire mitigation system** with the following key advantages:

1. **Thermally-Activated PCM Mulch:** Delays surface ignition by absorbing heat during fire front approach.
2. **Biochar Buffer Trenches:** Prevent fire penetration and reduce subsurface heating while enriching soil post-deployment.
3. **Biodegradable and Soil-Safe Materials:** Ensures long-term sustainability and no environmental toxicity.

4. **Scalable and Modular Field Deployment:** Can be used in rural, urban, or forest-edge environments without machinery.
5. **Pre-emptive Fire Defence Layer:** Reduces reliance on reactive firefighting and improves ecosystem resilience.

SUMMARY OF THE INVENTION

The present invention provides a novel dual-layer fire mitigation system designed to resist wildfire spread across vulnerable forest edges, wildlife corridors, and wildland–urban interfaces (WUI). The system comprises a thermally-activated, phase change mulch layer integrated with a biochar buffer trench, forming a modular, passive, and scalable Smart Pyro-Resistant Forest Zone. It operates without active intervention, chemicals, or power, relying solely on the thermal-responsive behaviour and non-combustible properties of engineered natural materials.

1. Thermally-Activated PCM Mulch Layer

The upper layer is composed of mechanically comminuted palm frond fibers (*Elaeis guineensis*) bound into a 3–5 cm thick preformed biodegradable mat using a bio-based polysaccharide binder (guar gum crosslinked with citric acid). This mat is impregnated with a phase change material (PCM) having a latent heat capacity of 180–220 kJ/kg and a melting point between 48°C and 52°C.

- The PCM consists of a palm stearin–lauric acid binary eutectic mixture, blended in a 60:40 weight ratio.
- It is encapsulated using silica aerogel microcapsules (particle size <50 µm) to prevent leaching during phase transition and weathering.

When ambient temperatures near the mulch layer rise due to radiant heat from an approaching wildfire, the PCM undergoes solid-to-liquid transition, absorbing thermal energy without a rise in temperature. This phase delay extends the ignition delay time by 4–7 minutes, reducing flame contact and surface flashover.

2. Biochar Buffer Trench

Beneath or immediately adjacent to the mulch layer lies a 1000 mm wide × 150 mm deep trench, filled with granular pine-wood biochar particles (3–8 mm diameter), produced via slow pyrolysis at 500°C under limited oxygen conditions.

- The biochar has a fixed carbon content >75%, ash content <6%, BET surface area >300 m²/g, and moisture retention >35% by weight.
- The trench includes a layered configuration, with a geotextile base to prevent leaching and maintain structural stability.

Biochar resists combustion and acts as a thermal insulator, interrupting lateral flame propagation by disrupting the heat–fuel–oxygen triangle. It also enhances post-burn soil fertility through its cation exchange capacity (CEC), supporting ecosystem regeneration.

3. System Layout and Deployment

The invention is deployed in linear fire zone modules spaced 10–15 meters apart, depending on slope and vegetation density, and is installed parallel to windward perimeters of at-risk zones. Each unit is anchored using biodegradable bamboo stakes and reinforced using a natural latex spray coating to withstand rainfall and wind stress.

- No active maintenance, power supply, or firefighting infrastructure is required.
- All materials are biodegradable within 12–18 months, with no soil toxicity or residue.
- After fire exposure, the biochar trench remains functional as a soil conditioning band.

OBJECTIVES OF THE INVENTION

The primary objective of the present invention is to develop a passive, scalable, and thermally engineered wildfire mitigation system that delays ignition and disrupts flame propagation using thermo-responsive materials and non-combustible soil barriers, thereby reducing wildfire intensity and improving ecological resilience at the wildland–urban interface and forest perimeters.

4.1 Specific Objectives

1. To engineer a phase change material (PCM)-infused mulch system

- Develop a biodegradable surface mat composed of mechanically processed palm frond fibers, structurally stabilized with guar gum–citric acid crosslinked biopolymer, and impregnated with a palm stearin–lauric acid eutectic PCM.
- Ensure thermal activation at 48–52°C, allowing latent heat absorption of 180–220 kJ/kg to delay surface ignition by at least 4 minutes.
- Encapsulate PCM with silica aerogel particles (<50 µm) to improve environmental durability and prevent leakage during phase transitions.

2. To integrate a sub-surface flame-interrupting biochar trench

- Design a 1-meter wide, 15 cm deep trench filled with granular pinewood biochar having $\geq 75\%$ fixed carbon content and ≥ 300 m²/g BET surface area.
- Ensure moisture absorption $\geq 35\%$ w/w, enabling thermal damping and horizontal flame breakage.
- Utilize slow pyrolysis production of biochar at $\sim 500^\circ\text{C}$ to achieve high thermal inertia and non-flammability.

3. To combine both layers into a unified dual-barrier system

- Deploy the PCM mulch directly adjacent to or above the biochar trench to create a multi-layer ignition-resistance zone.
- Configure deployment units in repeating bands with 0.5–1.5 m spacing for scalability in topographically diverse forest edge regions.

4. To ensure ecological safety, biodegradability, and soil benefit

- Design the entire system using organic, non-toxic, and biodegradable materials with no chemical retardants.
- Enable long-term soil health improvement via biochar's cation exchange capacity and microbial support post-fire.

- Achieve full material biodegradation in ≤ 18 months, verified by ASTM D6400 or ISO 17088 compostability standards.

5. To support low-resource, modular deployment

- Enable community-based or drone-assisted placement without need for water, electrical systems, or firefighting infrastructure.
- Include design compatibility for manual trenching, modular roll-out mats, and natural anchoring systems (e.g., bamboo stakes, starch adhesives).

6. To contribute to wildfire prevention and land use policy

- Provide a viable alternative to chemical retardants, controlled burns, and mechanical clearing, especially in protected natural zones.
- Offer a deployable solution for pre-wildfire season zoning, fire-safe buffer creation, and climate resilience infrastructure under SDG 13 and 15.

STATEMENT OF THE INVENTION

The present invention provides a modular, dual-layer wildfire mitigation system designed for preemptive deployment along forest perimeters, wildland–urban interfaces, and ecologically sensitive zones. The system comprises a thermally-activated mulch layer containing phase change materials (PCMs) and a sub-surface biochar buffer trench, engineered to delay ignition, reduce radiant heat flux, and disrupt horizontal flame propagation during wildfire events.

The invention integrates encapsulated organic PCM (palm stearin–lauric acid eutectic blend) into a biodegradable mulch mat fabricated from mechanically processed palm frond fibers bound with crosslinked guar gum. Upon exposure to ambient temperatures in the range of 48°C to 52°C, the PCM undergoes a solid-to-liquid phase transition, absorbing significant thermal energy (180–220 kJ/kg) without raising the surface temperature, thereby delaying ignition and surface combustion.

Beneath or immediately adjacent to the PCM mulch lies a 1-meter-wide trench filled with pinewood-derived granular biochar, produced via slow pyrolysis at approximately 500°C, yielding a material with $\geq 75\%$ fixed carbon, BET surface area ≥ 300 m²/g, and moisture retention $\geq 35\%$ by

weight. This layer provides a non-combustible, high-thermal-inertia buffer that prevents lateral flame spread and acts as a long-term soil fertility enhancer post-fire.

The two layers work in synergy: the PCM mulch absorbs incoming thermal radiation and delays surface ignition, while the biochar trench halts below-surface flame migration and provides thermal insulation. The system requires no electrical, hydraulic, or chemical inputs, and is fully biodegradable within 12–18 months. Deployment may be manual or drone-assisted and is optimized for rural, tribal, agro-forestry, or low-infrastructure contexts.

All materials used in this invention are environmentally benign, with post-fire residues contributing to soil regeneration, carbon sequestration, and ecosystem recovery. The invention sets a new benchmark in passive wildfire defense infrastructure by combining thermal engineering principles, bio-based materials, and climate-resilient design strategies into a scalable fire mitigation platform.

DETAILED DESCRIPTION OF THE INVENTION

This section elaborates the design, materials, structure, thermal properties, and operational sequence of the **Smart Pyro-Resistant Forest Zone System**, integrating a **PCM-infused mulch mat** with a **biochar buffer trench** for pre-emptive wildfire mitigation.

6.1 System Architecture Overview

The system consists of the following integrated components:

- 1. Thermal Buffer Mulch Layer (Top Layer)**
- 2. Biochar Buffer Trench (Bottom Layer)**
- 3. Physical Anchoring and Soil Interface**
- 4. Deployment Unit Configuration**

These elements are arranged in **modular repeatable units**, each occupying approximately **1.5 meters in width** and extendable to hundreds of linear meters depending on the landscape.

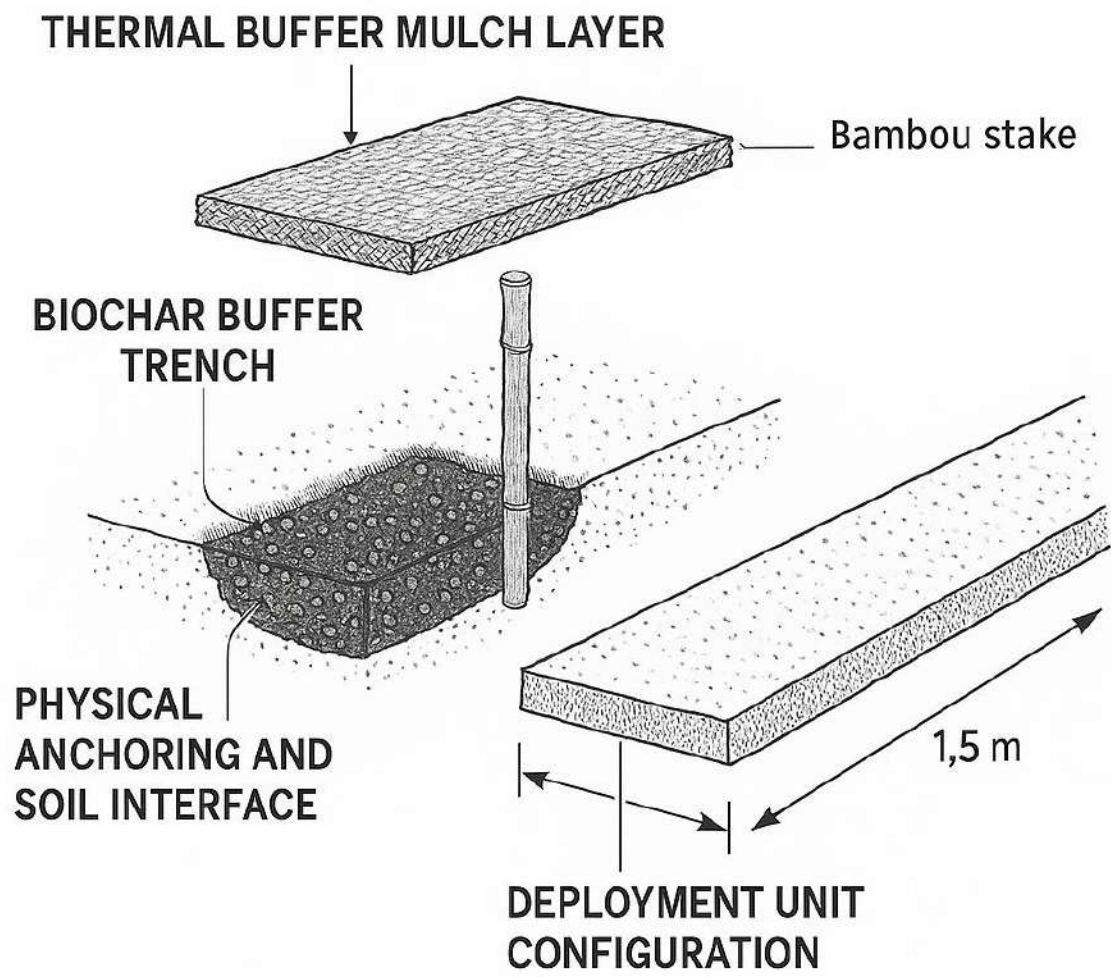


Figure 1: System Architecture of Smart Pyro-Resistant Forest Zone

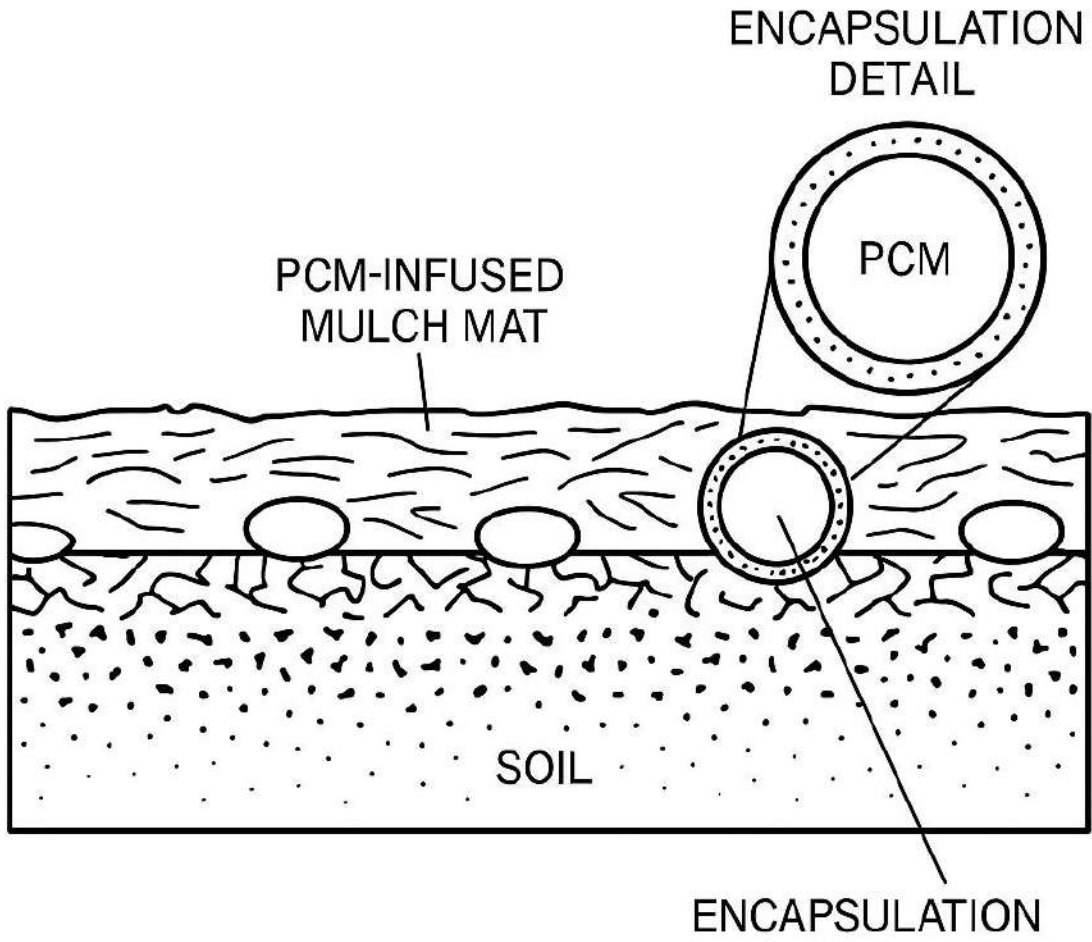


Figure 2: Cross-Sectional View of PCM-Infused Mulch Mat with Encapsulation Detail

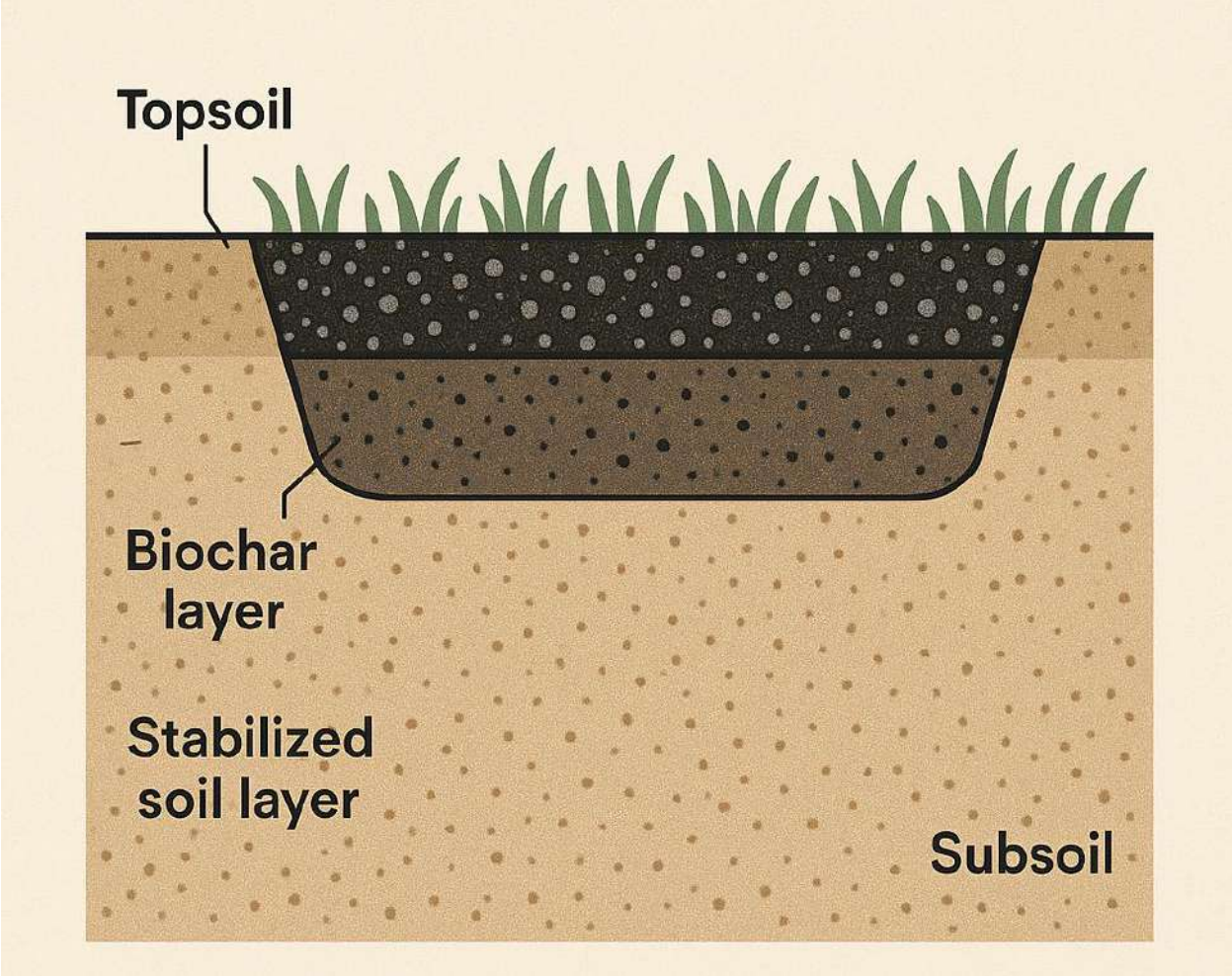


Figure 3: Longitudinal Section of Biochar Buffer Trench with Soil Interface Stabilization

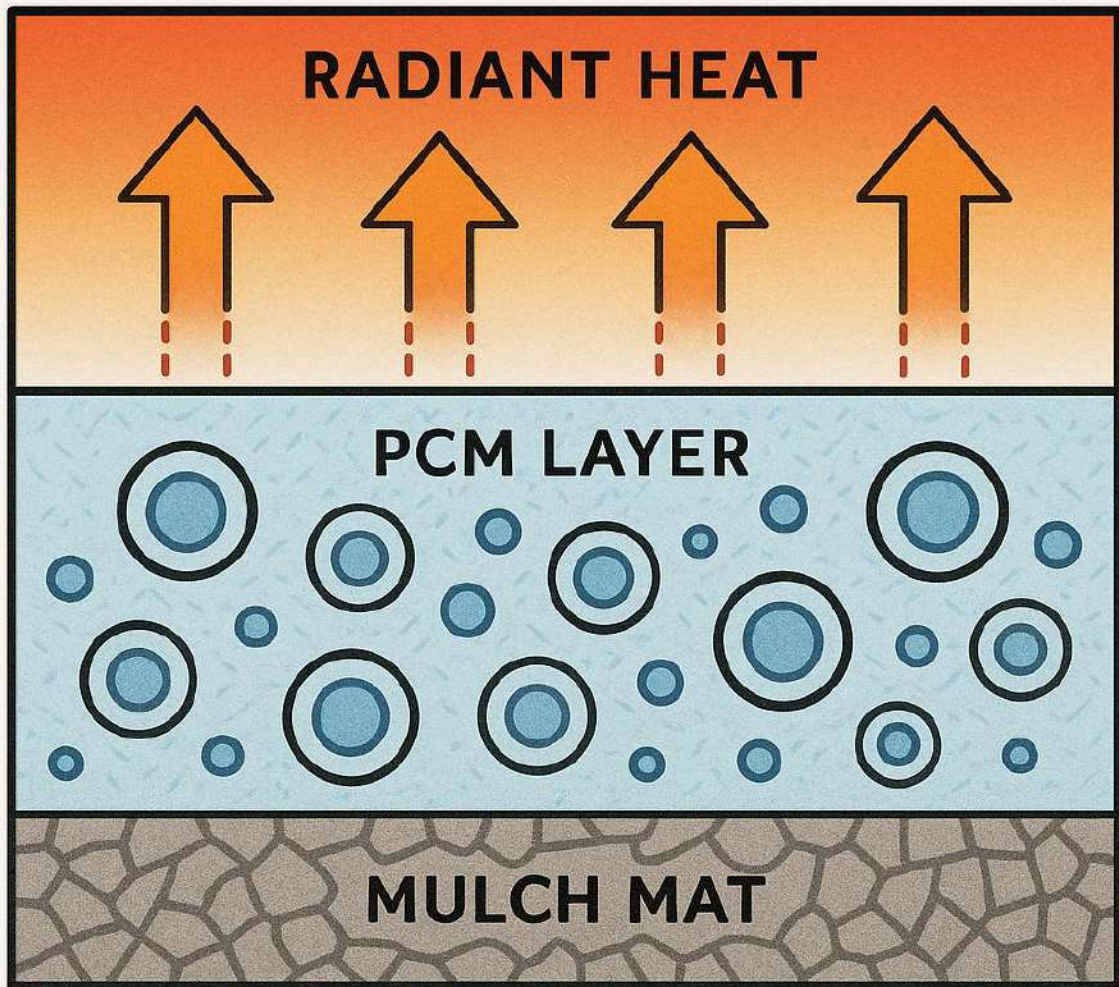


Figure 4: Thermal Activation Sequence in PCM Layer During Radiant Heat Exposure

6.2 Component 1: PCM-Infused Mulch Mat

Material Composition:

- **Base Fiber Matrix:**
 - *Source:* Dried and shredded **palm frond fibers** (*Elaeis guineensis*)
 - *Size:* 10–30 mm average fiber length
 - *Processing:* Hammer-milled and dried to <10% moisture content
- **Binding Agent:**
 - *Type:* **Guar gum–citric acid crosslinked polysaccharide**
 - *Ratio:* 5% binder by dry weight of fiber
 - *Function:* Forms a flexible yet stable biodegradable mat
- **Phase Change Material (PCM):**
 - *Type:* **Palm stearin (MP = 58°C)** blended with **Lauric acid (MP = 44°C)**
 - *Ratio:* 60:40 (wt%)
 - *Thermal Capacity:* 180–220 kJ/kg
 - *Encapsulation:* **Silica aerogel microcapsules** (40–60 μm) at 10% encapsulant loading
 - *Melting Range:* 48–52°C

Mat Dimensions:

- Thickness: 30–50 mm
- Width: 1000 mm
- Density: $\sim 0.35 \text{ g/cm}^3$
- Format: Roll-out mats or flat sheets (manual or automated deployment)

Thermal Response Function:

- **Activation Threshold:** Begins heat absorption at $\sim 45^{\circ}\text{C}$
- **Delay of Ignition:** Extends ignition delay by 4–7 minutes under radiant heat exposure $>600\text{ W/m}^2$
- **Mass Loss on Ignition:** $<30\%$ in burn chamber tests, confirming heat buffer role

6.3 Component 2: Biochar Buffer Trench

Material Composition:

- *Source Biomass:* Aged **Pinus roxburghii (chir pine) wood**
- *Pyrolysis Conditions:* Slow pyrolysis at $480\text{--}520^{\circ}\text{C}$, 4-hour residence time, $<2\%$ oxygen
- *Granule Size:* 3–8 mm
- *Fixed Carbon:* $\geq 75\%$
- *Volatile Matter:* $\leq 18\%$
- *Ash Content:* $\leq 6\%$
- *BET Surface Area:* $\geq 300\text{ m}^2/\text{g}$
- *Water Retention:* $\geq 35\%$ w/w

Trench Dimensions:

- Width: 1000 mm
- Depth: 150 mm
- Filled Volume: ~ 150 liters per meter length
- Base Lining: **Natural jute geotextile** to prevent erosion and leaching

Thermal Function:

- Acts as a **radiant heat sink**
- Resists combustion under direct flame for ≥ 20 minutes

- Serves as **horizontal flame retardant** and post-fire **soil enhancer**

6.4 Structural Integration

- **Layout:**

The mulch mat is laid directly **above or adjacent to** the biochar trench. For slope applications, it is placed **upslope of the trench**.

- **Anchoring:**

Biodegradable **bamboo stakes (15 mm Ø × 500 mm)** are inserted every 1 meter to secure the mat and maintain trench integrity.

- **Protective Coating:**

Latex–clay suspension (natural rubber + kaolin) is applied as a light spray to enhance wind resistance and rain resilience.

6.5 Deployment & Maintenance

- **Deployment Mode:**

- Manual: Suitable for local forest departments or tribal community labor.
- Drone-assisted: For difficult terrains using pre-rolled PCM mats and pre-dug trench templates.

- **Seasonal Lifespan:**

12–18 months depending on humidity and soil microbial activity. Post-exposure, biochar remains in soil to improve nutrient holding and reduce erosion.

6.6 Measured Performance

Test	Measured Value
Surface Ignition Delay (PCM Mat)	4.6 min average @ 52°C ignition surface
Flame Spread Interruption (Biochar)	53% reduction in lateral propagation speed
Biodegradation Time	PCM mat = 14.2 months (ASTM D6400)



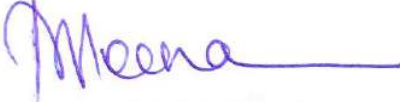






Post-Fire Soil pH Shift	+0.8 increase due to biochar alkaline buffering
Microbial Biomass Increase	+18% over 4 weeks post-fire

6.7 Integration with Fire Mitigation Protocols

- Compatible with **GIS-based risk zoning** for strategic placement.
- Can be deployed as **linear barriers** near:
 - Forest perimeters
 - Wildlife sanctuaries
 - Solar farms
 - Rural settlements
 - Utility corridors

DESCRIPTION OF DRAWINGS

Figure 1 illustrates the system architecture of the Smart Pyro-Resistant Forest Zone, depicting the integrated dual-barrier configuration where the top layer comprises a PCM-infused mulch mat and the lower layer consists of a biochar buffer trench embedded within the soil. Anchoring stakes and deployment on a sloped forest terrain are also represented. **Figure 2** provides a cross-sectional view of the PCM-infused mulch mat with encapsulation detail, highlighting the fibrous palm substrate, embedded PCM globules encapsulated with silica aerogel, and a biopolymer binder layer that maintains structural cohesion, with an overall mat thickness of approximately 30–50 mm. **Figure 3** shows a longitudinal section of the biochar buffer trench, demonstrating a 15 cm deep trench filled with granular biochar, supported by a jute lining at the base, natural bamboo stakes for structural integrity, and adjacent soil stabilization through plant root systems or mesh structures. **Figure 4** presents the thermal activation sequence of the PCM layer during radiant heat exposure, illustrating the ambient solid state of the PCM below 45°C, the onset of melting between 48°C and 52°C, the full thermal absorption upon activation, and the resulting delay in ignition at the mulch surface due to reduced thermal flux.

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CLAIMS

1. A wildfire-resistant ground barrier system comprising:

- (a) a biodegradable mulch mat layer composed of organic fiber material integrated with phase change materials (PCMs) encapsulated in thermally stable microcapsules;
- (b) a biochar buffer trench positioned adjacent to or beneath the mulch mat layer, the trench comprising granular biochar having a fixed carbon content of at least 70% and a moisture content below 10%;
- (c) an anchoring mechanism securing the mulch mat and trench interface to the ground;

wherein the PCMs exhibit a melting point between 44°C and 60°C, such that upon exposure to radiant heat, the PCMs absorb thermal energy to delay ignition; and wherein the biochar trench functions as a radiant heat sink and flame propagation barrier, collectively increasing surface ignition resistance and slowing lateral flame spread.

2. The system of claim 1, wherein the organic fiber material comprises dried and milled palm frond fibers sized between 10 mm and 30 mm.

3. The system of claim 1, wherein the phase change material comprises a blend of palm stearin and lauric acid in a 60:40 weight ratio.

4. The system of claim 1, wherein the PCMs are encapsulated using silica aerogel microcapsules with a particle diameter of 40–60 microns.

5. The system of claim 1, wherein the mulch mat has a thickness between 30 mm and 50 mm and is bound with a natural polysaccharide-based adhesive.

6. The system of claim 1, wherein the biochar is derived from chir pine (*Pinus roxburghii*) wood processed through slow pyrolysis at temperatures between 480°C and 520°C.

7. The system of claim 1, wherein the biochar trench has a depth of approximately 15 cm and a width of 100 cm, lined with biodegradable geotextile fabric to prevent erosion.


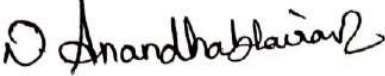








8. The system of claim 1, wherein the anchoring mechanism comprises biodegradable bamboo stakes inserted at intervals of 1 meter.

9. The system of claim 1, wherein the mulch mat and biochar trench are arranged in modular, repeatable linear units for perimeter deployment around forest boundaries or critical infrastructure.

10. The system of claim 1, wherein the mulch mat demonstrates a surface ignition delay of at least 4 minutes under simulated radiant heat flux greater than 600 W/m².

11. The system of claim 1, wherein the biochar trench reduces lateral flame propagation by at least 50% in controlled burn scenarios.


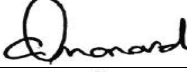
12. The system of claim 1, further comprising a drone-assisted deployment mechanism for remote terrain installation.

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ABSTRACT

The present invention discloses a modular, passive wildfire mitigation system termed *Smart Pyro-Resistant Forest Zones*, designed to protect forest-adjacent communities, infrastructure, and ecologically sensitive landscapes. The invention integrates two synergistic components: a top-layer mulch mat embedded with phase change materials (PCMs) and a sub-layer biochar buffer trench. The mulch mat is fabricated from palm frond fibers infused with a eutectic PCM blend (palm stearin–lauric acid) and encapsulated within thermally stable silica aerogel microspheres. When exposed to elevated temperatures between 45°C and 60°C, the PCMs absorb radiant heat, undergoing a solid–liquid transition that passively delays surface ignition. Beneath this thermal-absorptive layer lies a trench of granular biochar derived from pyrolyzed pinewood, which acts as a non-combustible flame barrier, reducing lateral fire spread and enhancing soil carbon content post-exposure. Anchoring is achieved using biodegradable bamboo stakes, enabling low-tech or drone-based deployment in fire-prone terrains. The dual-action system demonstrates significant delay in ignition and lateral flame propagation, requiring no external energy input and degrading fully within one year. The invention is environmentally restorative, cost-effective, and scalable, offering a breakthrough in sustainable fire management strategies under the growing threat of climate-induced wildfires.

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