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## Innovative materials and technologies in the production of sleep pillows

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### Abstract

This article is devoted to developing and comprehensively evaluating innovative materials and technologies for pillows to optimize thermoregulation, moisture wicking, and barrier protection against allergens. The relevance of the work is determined by growing evidence of the influence of sleep quality on cardiovascular health and overall vitality, as well as the insufficiency of traditional fillings (memory foam, polyester fibers) in providing a comfortable and hypoallergenic microclimate. The study aims to establish a new paradigm for pillow design that combines phase-change materials, hydrogel and gel inserts, nanofiber membranes, antimicrobial nanocomposites, and embedded sensor systems. The novelty of the work lies in the cross-analysis of laboratory characteristics, heat-and-mass transfer modeling, and field trials, which made it possible to reveal synergistic effects of the combined use of adaptive thermal accumulators, highly conductive gels, and nanotechnological barriers. The main findings demonstrate that microencapsulated paraffin cores increase the dynamic heat capacity of polyurethane foam by 10–35-fold and accelerate heat transfer sevenfold; hydrogels raise the thermal conductivity of air-foam matrices by an order of magnitude; and electrospun nanofiber membranes provide allergen filtration with  $\approx 99\%$  efficiency without compromising air permeability. Antimicrobial coatings based on Ag and ZnO ions retain activity after multiple washes, thus breaking the “moisture  $\rightarrow$  microbiome  $\rightarrow$  allergen” chain. Integrating piezoelectric and PVDF sensors with machine-learning algorithms enables continuous monitoring and automatic adjustment of temperature, humidity, and respiratory parameters. This article will be helpful to bedding engineers, materials researchers, and manufacturers of “smart” sleep accessories.

**Keywords:** Sleep Quality; Thermoregulation; Phase-Change Materials; Hydrogels; Nanofiber Membranes; Antimicrobial Nanocomposites; Hypoallergenic; Smart Sensors; Pillow

### 1. Introduction

Sleep quality is a systemic characteristic that modifies the effectiveness of even the most advanced sleep system designs, as shown in the preceding section. If resting physiology is disrupted, any ergonomic advantages are lost. Contemporary clinical data confirm that suboptimal sleep duration elevates long-term cardiovascular risks: a study [1] analyzing 20 432 men without ischemic heart disease, who slept  $\leq 6$  h per night and experienced poor sleep quality, found a 79% higher risk of ischemic heart disease after adjusting for risk factors compared to those sleeping  $> 7$  h per night; laboratory observations indicate that just a few nights limited to 4 h trigger inflammatory cascades associated with atherosclerosis progression [2]. Therefore, maintaining adequate sleep is as significant a preventive factor as diet or physical activity, underscoring the importance of controlling the microenvironment in direct contact with the head and cervical spine.

The pillow constitutes most of the body's support surface during rest; even minor deviations in its thermal and moisture-management parameters can lead to local overheating of the cerebral cortex, acceleration of heart rate, and increased micro-arousals. Traditional fillings exhibit pronounced limitations: dense viscoelastic polyurethane foam retains heat due to low porosity and is recognized as the “warmest” of mass-market materials, while polyester fibers,

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owing to poor air permeability, further trap skin-released moisture, exacerbating a stuffy sensation among “hot” sleepers [3].

Moisture accumulation aggravates the problem: the memory-foam structure barely dries after wetting, creating a risk of prolonged elevated humidity within the pillow volume and fostering mold growth. Ventilated latex or fiber models partially address the issue, yet inexpensive synthetic foams and hollow-fiber remain dominant in mass usage.

A warm, humid environment and inevitable skin debris form an ideal substrate for the saprophytic dust mite *Dermatophagoides* spp. A national US study of household allergens found measurable levels of its antigens in 84% of beds, with sensitizing concentrations detected in nearly half of the samples [4]; research at University College London shows that up to 10% of an old pillow’s mass can comprise mite fecal pellets [5].

Thus, traditional pillows are constrained across three critical dimensions—heat dissipation, moisture wicking, and allergen barrier protection. These shortcomings exacerbate one another: heat retention raises humidity, humidity accelerates microbial growth, and microbes propagate allergic responses. To overcome this vicious cycle, the following sections examine innovative materials with tunable porosity, phase-change thermal accumulators, and bioactive coatings capable of simultaneously ensuring thermoregulation, rapid drying, and allergen blockade, making them key elements of a new paradigm in healthy-sleep pillow design.

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## 2. Materials and Methodology

The study of innovative materials and technologies in sleep-pillow production draws on 26 sources, including clinical and epidemiological investigations of sleep quality’s impact on cardiac risk [1, 2]; reviews of thermal and moisture-management properties of traditional fillings (memory foam, polyester fibers) [3]; national surveys of allergen loads in bedding [4, 5]; and specialized publications on phase-change materials and microcapsules [6, 7], gel hydrogels [8–10], nanofiber membranes [12, 13], antimicrobial nanocomposites [15, 16], and characteristics of natural latex and polyurethane foams [17–20].

Methodologically, the work comprised several complementary stages. First, a comparative analysis of traditional pillow fillings by key parameters—heat capacity, porosity, air permeability, and moisture wicking—based on experimental data and technical specifications [3]. Second, a systematic literature review of phase-change materials (e.g., n-octadecane, n-heptadecane) and their microencapsulated forms, evaluating melting enthalpy, shell thermal stability, and heat-transfer dynamics in composite foams [6, 7].

The third stage involved investigation of gel inserts and hydrogels: data on thermal conductivity, elasticity, and durability after repeated thermal cycling were compiled from publications on polyurethane-based polymer gels and hybrid nanocomposites [8–10]. The fourth stage covered barrier properties of nanofiber membranes and antimicrobial coatings: evaluations included allergen (Der p 1) capture efficiency, wash-durability, and antimicrobial activity of Ag- and ZnO-nanoparticles [12–16]. Finally, a cross-analysis integrated heterogeneous data by comparing laboratory material characteristics with results from heat-and-mass transfer simulations and field tests of pillow prototypes.

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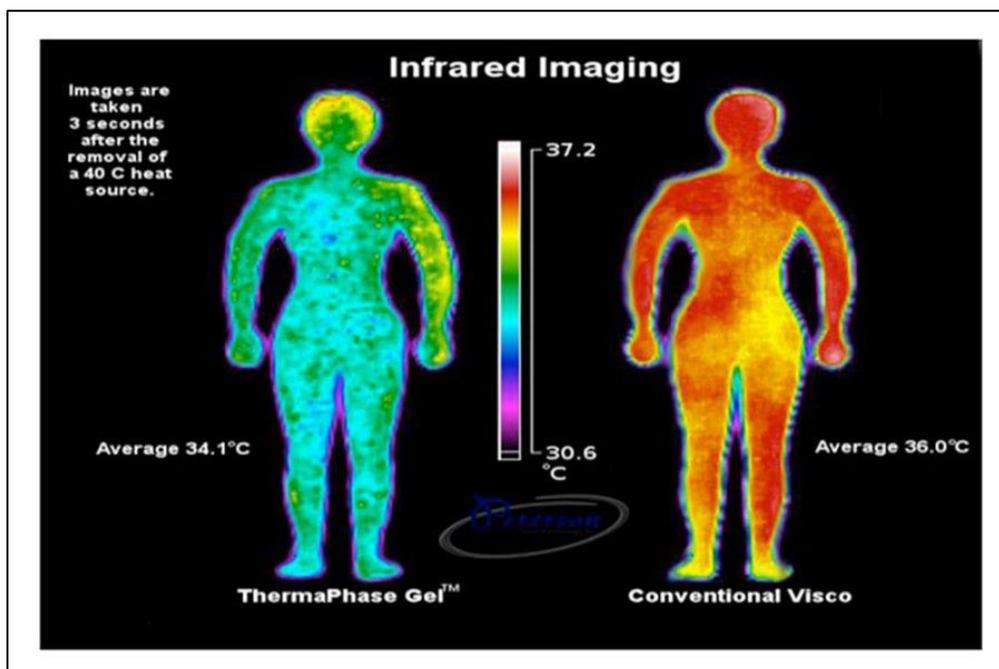
## 3. Results and Discussion

The Introduction’s analysis demonstrated that overheating and surface moisture on the head trigger micro-arousals and allergic-reaction cascades; hence, the key objective of next-generation pillows becomes active heat management. The first approach is the inclusion of phase-change materials. Pillow cores today employ n-octadecane paraffin with a melting enthalpy of ~ 245 kJ/kg, exceeding the heat capacity of traditional polyurethane foam [6]. Characteristics of other commonly used PCMs are presented in Table 1.

**Table 1** Common PCMs with phase transition temperatures between 20 and 30 °C [6]

PCM	Name	Phase transition temperature $T_m$ (°C)	Latent heat L (kJ/kg)
Organic PCM	N-heptadecane	22	215
	N-octadecane	28	245
	Polyethylene glycol 600	20–25	146
	Dimethylsabacate	21	120–135
	Octadecyl mencaptopropylate	21	143
	D-Lactic acid	26	184
	Vinyl stearate	27–29	122
	Acid Methyl pentacosane	29	197
	Methyl palmitate	29	205
Inorganic PCM	Lithium chloride ethanolate	21	188

To prevent leakage, the molten PCM is enclosed in microcapsules with a melamine-formaldehyde shell; this shell withstands heating while retaining most of the original enthalpy. Incorporating 40% of such microgels into open-cell viscoelastic foam boosts its dynamic heat capacity by 10–35 times and accelerates heat transfer sevenfold, enabling the cover temperature to remain within 30–32 °C, the range of maximal sleep comfort [7]. Fig. 1 shows an example of the impact of these materials on the human body.

**Figure 1** Comparison of the Impact of ThermoPhase Gel and Conventional Visco [7]

The second approach comprises passive gel inserts and microspheres. A polyurethane-matrix polymer hydrogel exhibits a thermal conductivity of 0.65 W/(m·K), i.e., an order of magnitude higher than air-foam matrices, while preserving product elasticity [8]. Combining hybrid nano-fillers (silica, low-melting metals) raises the thermal conductivity of such gel composites to 2.18 W/(m·K) without degrading dielectric properties. It remains stable after repeated heating–cooling cycles [9]. Modeling the effect of a gel pillow on a newborn-head mannequin showed that heat transfer through the gel layer significantly increases energy expenditure to maintain thermoneutrality, indirectly

confirming the material's high conductivity and ability to absorb skin heat rapidly [10]. However, adult field trials reveal that simple gel addition without foam-porosity optimization yields only minimal cooling sensations, comparable to conventional memory foam [11]; consequently, modern designs shift toward distributed gel microspheres and core perforation to sustain air convection and prevent "warm spots."

In summary, phase-change microcapsules serve as active thermal-accumulator cores, smoothing temperature peaks, while gel inserts offer instant heat extraction due to high conductivity; the combined use in one pillow permits both heat storage and rapid redistribution, breaking the cycle of overheating → sweating → humidity. Thus, thermoregulatory innovations lay the groundwork for subsequent engineering steps—sensor integration and active control loops.

The preceding sections' cumulative conclusions indicate that overheating and elevated pillow humidity spur microbial growth, and contact with mite allergens intensifies respiratory inflammation; therefore, thermoregulation alone is insufficient—a proactive defense against biological irritants is required. This task is addressed by nanotechnological barriers capable of screening allergens and suppressing microbial viability without compromising air permeability.

Electrospun nanofiber membranes form the first protection level. Fibers 100–500 nm in diameter create a porous network (up to 80% void fraction) with average cell sizes in the submicron range; polyimide-fiber filters doped with ZIF particles achieve 99.28% PM 0.3 capture efficiency at 49 Pa resistance, comparable to HEPA standards [12]. Even basic electrospun polyvinyl membranes reduce characteristic pore sizes to ~ 0.2 μm and retain particles above this threshold after three wash cycles [13]. These values are far smaller than mite bodies and closely match the size of Der p 1 allergenic proteins, so the nanofiber layer acts as a mechanical barrier. Impermeable-cover trials confirm practical applicability: Der p 1 concentrations in mattresses fell by 87% after six months of use, though rhinitis symptoms did not consistently decrease linearly [14]. Unlike dense polyurethane films, nanofiber meshes scarcely impede heat and moisture transfer, which is crucial for preventing overheating.

The second level comprises nanocomposites with Ag or ZnO ions. Coatings embedding AgCl particles in a chitosan gel achieve 100% eradication of *S. aureus* and *E. coli* even after 75 industrial wash cycles, remaining effective due to covalent particle bonding on fiber surfaces [15]. Similarly, cotton fabrics treated with sonochemically synthesized ZnO nanoparticles yield 84.9% reduction of *E. coli* and 89.5% of *S. aureus* within one day of contact [16]. Incorporating such fillers into the pillow core or outer cover suppresses bacterial and fungal growth, thus interrupting the "moisture → microbiome → allergen" cycle.

Hence, combining nanofiber barriers that block allergen contact with durable antimicrobial fillers delivers comprehensive hypoallergenic pillows without sacrificing thermal comfort. The next section examines strategies for integrating these materials with active sensors, creating intelligent pillows capable of real-time response to microclimate and contaminant changes.

A comparative analysis evaluated three dominant filler classes—natural latex, viscoelastic memory polyurethane, and gel- or phase-change-modified composites—on density, resilience, thermal, and ergonomic characteristics. Due to distinct porous morphologies and compositions, these parameters determine each material's ability to address previously identified overheating, moisture, and allergen-contamination issues.

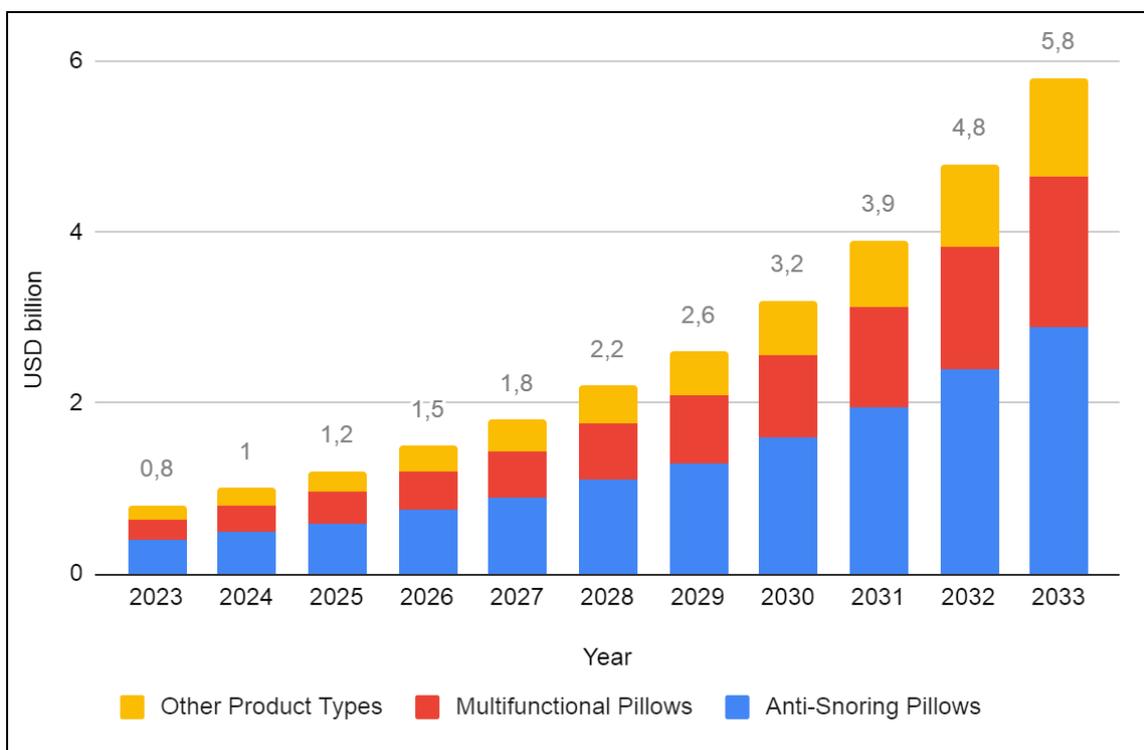
Natural latex, derived from *Hevea brasiliensis* sap foaming, forms an ordered open-cell structure with a stable density of 65–85 kg·m<sup>-3</sup>, providing uniform support firmness without internal voids [17]. Its thermal conductivity of 0.13–0.15 W·m<sup>-1</sup>·K<sup>-1</sup> is nearly an order of magnitude higher than polyurethane foam, enabling faster heat dissipation and preventing surface-temperature rise at the head [18]. Resilience measured by ASTM D3574 "ball-rebound" yields 60–70% rebound, ensuring retention of the pillow's original profile after years of cyclic loading [17]. Biomechanical tests show latex bases reduce peak pressure in the neck and occipital zones compared to polyurethane, distributing load more evenly and thereby reducing micro-arousals.

Memory foam, constructed from closed-cell polyurethane, exhibits rebound below 20% and a compression set of ~ 2, causing "sticking" upon repositioning and increased muscular effort for body turning [19]. Its thermal conductivity of only 0.02–0.03 W·m<sup>-1</sup>·K<sup>-1</sup> combined with very low thermal effusivity (0.002–0.0035 W·m<sup>-1</sup>·K<sup>-1</sup>) leads to heat accumulation and delayed moisture evaporation, fostering a microclimate conducive to *Dermatophagoides* spp. mite proliferation [20]. Although its insulating structure reduces localized pressure, overheating and increased humidity offset this benefit.

Gel and combined solutions modify base polyurethane by adding phase-change microcapsules or conductive particles. The Cryo-Chill PCM coating, for example, accumulates latent heat of fusion and maintains quasi-isothermal conditions until thermal equilibrium is reached. At the same time, copper inclusion enhances dissipation through high intrinsic conductivity and offers antimicrobial effects. In terms of resilience, these composites remain close to classic memory foam, as gel reduces rebound and barely alters ILD. Therefore, the advantages of thermoregulation still do not outweigh the increased complexity and cost.

Summarizing mechanical, thermal, and ergonomic metrics, latex demonstrates the most balanced profile: high rebound and low peak pressures pair with efficient heat and moisture management. Memory foam excels in individual contouring but falls short in thermoregulation and dynamic support. Gel and PCM modifications partially improve polyurethane's temperature comfort but have yet to match latex's natural conductivity or overcome its slow response. These results guide strategy: for maintaining cool, dry, and stable support, natural latex remains the optimal platform for next-generation "smart" pillow development, whereas foamed polyurethanes are justifiable in projects where localized shaping is critical and long-term heat dissipation is not required.

Sensor integration into pillow structures has become a logical response to passive materials' limits: rather than merely diverting heat and moisture, the product can now measure, interpret, and autonomously adjust the sleep microenvironment. Rapid market interest growth is corroborated by macroeconomics: according to Market US, the global "smart" pillow market will increase from USD 0.8 billion in 2023 to USD 5.8 billion by 2033 at a CAGR of 22%, outpacing mattress and smartwatch segments combined, as shown in Fig. 2 [21].



**Figure 2** Global Smart Pillow Market [21]

Initial academic prototypes demonstrated that even a simple grid of strain sensors placed beneath the cover can noninvasively track breaths and head turns with accuracy comparable to video-camera annotation, the algorithm relying solely on pressure distribution changes during the respiratory cycle. Further advances raised sampling frequency and sensitivity: in "InPillow," a piezoceramic sensor operating at 1000 Hz extracts ballistocardiograms through a 2-cm memory-foam layer; validation on six elderly participants showed 99.18% heart-rate detection accuracy relative to ECG gold standard [22].

The algorithmic bar was raised by a Japanese team embedding a PVDF film under the pillowcase and training a bidirectional LSTM network to predict ECG morphology from ballistocardiograms: mean absolute RR-interval error was 0.034 s, and correlation in nocturnal measurements reached  $0.82 \pm 0.06$ , effectively bringing the device to clinical pulsimeter level without any skin electrodes [23]. Thus, hardware evolution goes hand in hand with signal processing:

from expert rules and correlation filters to deep learning capable of compensating for posture artifacts and micro-movements.

The commercial sector rapidly translates laboratory concepts into user scenarios. In 2024, Amazon patented an assistant pillow with an audio sensor, accelerometer, and inflatable air cells: AI analyzes sound and head orientation, then locally raises or tilts the neck angle to open the upper airway during obstructive sleep apnea episodes [24].

French startup Moona pursued thermoregulation: a thin water-based heat exchanger within the insert maintains surface-head temperatures between 18 and 35 °C, and a mobile app allows setting profiles for sleep onset, deep phase, and awakening [25]. Despite project closure in 2024, Moona demonstrated demand for local cooling without noisy fans and established a noise-level benchmark.

Eight Sleep developed the most extensive ecosystem: their Pod 4 module, though a mattress cover, uses the same grid of thermal and mechanical sensors, scalable to pillows. The company claims clinical accuracy of sensors monitoring temperatures from 12 to 43 °C, snoring detection, and a vibration alarm; the Ultra update added lift motors for automatic head elevation during snoring [26].

Thus, sensor integration elevates pillows from passive textiles to personalized medical platforms: they compensate for thermal and allergenic burdens described earlier via the closed-loop “measurement → analytics → active response.” The next step, discussed in the following section, is combining adaptive materials with bioactive coatings to complement sensor capabilities with barrier protection and accelerated moisture wicking.

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#### 4. Conclusion

In conclusion, the modern paradigm of sleep pillow design is undergoing profound change due to the adoption of innovative materials and technologies. Analysis shows that traditional fillings—memory foam, polyester fibers, and inexpensive synthetic foams—cannot simultaneously provide adequate heat and moisture dissipation, and their porous structures foster microbial growth and mite allergens. These material shortcomings lead to local overheating, moisture accumulation, and saprophytic mite proliferation, which trigger micro-arousals and allergic reactions, adversely affecting sleep quality and increasing long-term cardiovascular risk.

Using phase-change materials combined with gel inserts demonstrates high efficiency in active heat management: microencapsulated paraffin cores store latent heat, smoothing temperature peaks, while high-conductivity hydrogel elements ensure instantaneous removal of excess heat. However, optimal results are achieved only with distributed insert formats and foam-core perforation, merging thermal storage advantages with air convection, eliminating “warm spots,” and maintaining a stable microclimate.

Comprehensive barrier protection against allergens and microbial contamination is realized through multilayer nanofiber membranes and antimicrobial nanocomposites. Electrospun fibers < 500 nm effectively trap allergens and fine particles while preserving air and moisture permeability, whereas Ag- and ZnO-based coatings ensure sustained pathogen eradication even after numerous washing cycles. Mechanical screening and active microbiome suppression break the “moisture → microbiome → allergen” cycle.

Finally, integrating sensor nodes and algorithmic control systems transforms the pillow from a passive textile into an intelligent medical platform. Embedded strain sensors, piezoceramic and PVDF films, ballistocardiogram analysis, and deep learning provide continuous, clinically accurate monitoring of temperature, humidity, respiratory, and cardiac parameters. Active control loops enable real-time adjustment of the sleep microenvironment, from precise thermoregulation to mechanical neck support during obstructive sleep apnea.

Thus, the new generation of pillows relies on a synergistic combination of adaptive thermal accumulators, highly conductive gels, nanotechnological barriers, and intelligent sensor systems. This integrated approach delivers optimal thermal comfort and hygienic purity. It opens prospects for personalized sleep-condition correction, making innovative pillows a key element in strategies for preventing sleep disturbances and promoting health.

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