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# Sustainable Wellness Textiles: Fragrance-Integrated Bamboo–Hemp Underwear for Odor Management and Skin Comfort

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**ABSTRACT**
*The growing demand for sustainable, skin-friendly, and wellness-oriented apparel has accelerated research into functional textiles that extend beyond basic comfort and aesthetics. Among natural fibers, bamboo and hemp have gained increasing attention for underwear applications due to their excellent breathability, moisture management, biodegradability, and inherent antimicrobial properties. However, while these fibers effectively reduce microbial growth and odor formation, they do not provide sustained freshness or sensory enhancement without additional functional treatments. In recent years, fragrance-integrated textiles have emerged as a promising solution for improving wearer comfort, hygiene, and psychological well-being through controlled aroma release. This review critically examines recent advances in fragrance-integrated bamboo–hemp underwear, focusing on odor management, antimicrobial enhancement, and skin comfort. The fundamental mechanisms of odor generation in intimate apparel are discussed, followed by a comprehensive analysis of bamboo and hemp fiber properties relevant to next-to-skin applications. Advanced fragrance delivery technologies including microencapsulation, cyclodextrin-based host–guest systems, and essential oil finishes are systematically reviewed with emphasis on durability, wash fastness, skin safety, and controlled release behavior. The synergistic integration of fragrance systems with antimicrobial finishes such as zinc oxide, chitosan, and probiotic treatments is highlighted as a dual-action strategy for long-lasting odor prevention and sustained freshness.*
*In addition, the influence of fabric structures, laundering durability, sensory performance, and regulatory considerations is discussed in the context of intimate apparel. Current research limitations, industrial challenges, and future perspectives are identified, emphasizing the need for scalable, skin-safe, and environmentally responsible fragrance technologies. This review provides a comprehensive framework for the development of next-generation sustainable wellness underwear, offering valuable insights for researchers, textile manufacturers, and apparel brands seeking to combine natural fibers, functional performance, and sensory innovation.*

***Keywords:*** *Bamboo–Hemp Textiles, Functional Underwear, Fragrance Microencapsulation, Odor Control, Antimicrobial Finishes, Wellness Textiles, Sustainable Apparel.*

## 1. Introduction

The global textile and apparel industry is undergoing a significant transformation driven by growing consumer awareness of sustainability, health, and personal well-being. Traditional performance enhancement in textiles has largely focused on durability, aesthetics, and cost efficiency; however, modern consumers increasingly demand apparel that supports hygiene,

comfort, and psychological wellness, particularly in garments designed for prolonged skin contact. Among various apparel categories, underwear represents one of the most critical segments due to its continuous exposure to perspiration-prone and microbiologically active areas of the human body. Consequently, odor formation, moisture accumulation, microbial growth, and skin irritation remain persistent challenges in intimate apparel designs [1].

Conventional underwear materials, predominantly based on synthetic fibers such as polyester, nylon, and elastane blends, exhibit limited breathability and moisture management, which often exacerbates bacterial proliferation and odor retention. While cotton remains widely used due to its softness and absorbency, it lacks inherent antimicrobial functionality and often fails to provide long-lasting freshness under high perspiration conditions. These limitations have intensified interest in alternative natural fibers capable of delivering superior moisture regulation, breathability, and hygiene without compromising comfort or environmental sustainability [2, 3].

In this context, bamboo and hemp fibers have emerged as promising candidates for next-generation functional underwear. Both fibers are renewable, biodegradable, and associated with lower environmental footprints compared to conventional textile raw materials. Bamboo fibers are recognized for their softness, moisture absorption, and inherent antimicrobial behavior, while hemp fibers offer excellent breathability, durability, ultraviolet (UV) resistance, and resistance to microbial growth. When blended, bamboo and hemp fibers form a synergistic textile system that balances softness and strength while naturally reducing odor formation. However, although these fibers contribute to odor mitigation, they do not provide sustained sensory freshness or controlled fragrance release without additional functional treatments [4, 5].

Recent advances in fragrance-integrated textiles have introduced new possibilities for enhancing wearer comfort, hygiene, and psychological well-being. Fragrance technologies such as microencapsulation, cyclodextrin-based host–guest systems, and essential oil finishes enable controlled aroma release triggered by body heat, friction, and movement. When applied to underwear fabrics, these technologies offer prolonged freshness, aromatherapeutic benefits, and enhanced user confidence. Nevertheless, the integration of fragrance systems into intimate apparel requires careful consideration of skin safety, wash durability, antimicrobial compatibility, and sustainability—factors that are often overlooked in existing scented textile products [6, 7].

Despite growing research interest in fragrant textiles, current literature largely focuses on applications in bedding, medical textiles, and cosmetic–textile hybrids, with limited attention paid to underwear-specific requirements. Furthermore, systematic reviews addressing the integration of fragrance delivery systems with natural fiber-based underwear—particularly bamboo–hemp blends—remain scarce. This review aims to fill this critical knowledge gap by providing a comprehensive and critical assessment of fragrance-integrated bamboo–hemp underwear, emphasizing odor management, antimicrobial enhancement, skin comfort, and sustainability [8, 9].

**2. Sustainable and Wellness-Oriented Textiles: Conceptual Framework**

Sustainable textiles are increasingly defined not only by their environmental performance but also by their contribution to human health and well-being. Wellness-oriented textiles represent a rapidly growing research and commercial domain that integrates functional finishes, bioactive materials, and sensory enhancement into textile structures. These textiles aim to improve physical comfort, hygiene, and psychological relaxation while minimizing environmental impact and potential health risks [10].

Wellness textiles often incorporate functionalities such as moisture management, antimicrobial activity, UV protection, thermoregulation, and fragrance release. Among these, fragrance integration has gained particular attention due to its ability to influence mood, reduce stress, and enhance the perceived cleanliness and freshness of garments. Aromatherapy studies have demonstrated that fragrances such as lavender, chamomile, citrus, and sandalwood can positively affect emotional states, reduce anxiety, and improve overall comfort. When incorporated into textiles, these fragrances transform garments into interactive systems that respond dynamically to wearer activity [11].

From a sustainability perspective, wellness textiles increasingly prioritize natural fibers, bio-based finishes, and non-toxic functionalization methods. Bamboo and hemp align well with this paradigm due to their rapid renewability, low pesticide requirements, and biodegradability. Integrating fragrance delivery systems with these fibers presents an opportunity to create multifunctional textiles that support both environmental and human well-being. However, achieving this integration requires a careful balance between performance durability, skin compatibility, and ecological responsibility.

In intimate apparel, the wellness textile concept is particularly relevant. Underwear must maintain hygiene under constant moisture exposure while remaining soft, breathable, and non-irritating. Fragrance-integrated bamboo–hemp underwear exemplifies the convergence of sustainability and wellness by combining natural fiber benefits with controlled aroma release and antimicrobial enhancement. This convergence positions such textiles as a new category of functional apparel designed to address both physiological and psychological needs [12].

## 3. Bamboo and Hemp Fibers for Intimate Apparel Applications

### 3.1 Bamboo Fiber: Structure and Functional Properties

Bamboo fiber has gained substantial attention in textile applications due to its softness, moisture absorbency, and eco-friendly reputation. Regenerated bamboo fibers, often produced via viscose or lyocell processes, exhibit a smooth surface and round cross-section that contributes to their silk-like hand feel. Bamboo fibers demonstrate high moisture regain, enabling efficient sweat absorption and rapid moisture transport away from the skin. This property is particularly advantageous for underwear, where prolonged moisture accumulation can lead to discomfort and microbial growths [13].

One of the most frequently cited advantages of bamboo fiber is its inherent antimicrobial activity, commonly attributed to a bioactive compound known as “Bamboo Kun.” This natural agent inhibits the growth of odor-causing bacteria, thereby reducing microbial decomposition of sweat components. As a result, bamboo-based fabrics exhibit improved odor resistance compared to conventional cotton textiles. Additionally, bamboo fibers possess excellent breathability and thermal regulation properties, allowing them to remain cool in warm conditions and comfortable during extended wear [14].

### 3.2 Hemp Fiber: Breathability and Durability

Hemp fiber is one of the strongest and most durable natural fibers, characterized by high tensile strength, abrasion resistance, and dimensional stability. Its porous structure facilitates excellent air permeability and moisture vapor transmission, making hemp particularly suitable for garments exposed to high perspiration levels. Hemp fibers also exhibit natural resistance to bacterial and fungal growth due to the presence of phenolic compounds and other bioactive constituents [15].

From a sustainability perspective, hemp cultivation requires minimal water and agrochemicals, contributing to its low environmental footprint. Hemp fibers also provide inherent UV protection and maintain structural integrity over repeated laundering cycles. However, hemp

fibers alone may exhibit stiffness and limited softness, which can reduce comfort in intimate apparel unless blended with softer fibers.

3.3 Synergistic Benefits of Bamboo–Hemp Blends

Blending bamboo and hemp fibers combines the softness and moisture absorption of bamboo with the strength, breathability, and durability of hemp. This synergy results in fabrics that are comfortable, breathable, and resistant to odor formations [16]. Bamboo–hemp blends demonstrate enhanced dimensional stability, improved mechanical performance, and superior comfort compared to single-fiber systems. Importantly, both fibers contribute inherent antimicrobial properties, reducing reliance on chemical finishes for basic hygiene.

Despite these advantages, bamboo–hemp fabrics alone cannot provide sustained fragrance or long-term freshness under repeated wear and laundering. This limitation underscores the need for integrating advanced fragrance delivery and odor-control technologies, which will be explored in subsequent sections of this review.

**4. Odor Formation Mechanisms in Underwear: Scientific Basis and Textile Relevance**

Odor development in underwear is governed by a complex interplay between human physiology, microbial activity, and textile material properties rather than by perspiration alone. Human sweat is largely odorless at the time of secretion; however, it contains a mixture of water, electrolytes, fatty acids, urea, ammonia, and other organic compounds that provide an ideal substrate for microbial metabolisms [17]. When underwear remains in close contact with sweat-prone areas of the body, elevated temperature and humidity create favorable conditions for bacterial growth, leading to the biochemical degradation of sweat components and the subsequent generation of malodorous volatile organic compounds.

The primary microorganisms responsible for textile-related body odor include species of *Corynebacterium*, *Staphylococcus*, and *Micrococcus*. These bacteria metabolize sweat-derived lipids and proteins into low-molecular-weight fatty acids, sulfur-containing compounds, and nitrogenous by-products such as ammonia. Compounds such as isovaleric acid, butyric acid, and thioalcohols possess particularly low odor thresholds, making them readily detectable even at trace concentrations. Once formed, these odor-causing molecules can adsorb strongly onto textile fibers, resulting in persistent malodor that is difficult to remove through conventional launderings [18].

Fiber chemistry plays a critical role in odor retention and release. Synthetic fibers such as polyester and nylon exhibit hydrophobic surfaces that preferentially bind oily sweat components and hydrophobic odor molecules. As a result, these fibers often retain odors even after repeated washing. Furthermore, their low moisture absorbency leads to prolonged surface wetness, which further promotes bacterial proliferation. In contrast, natural fibers such as bamboo and hemp exhibit higher moisture regain, allowing sweat to be absorbed and distributed throughout the fabric structure, thereby facilitating evaporation and reducing localized microbial growths [19].

Although bamboo and hemp fibers demonstrate inherent antimicrobial behavior that suppresses bacterial activity to some extent, they do not completely prevent odor formation, particularly during prolonged wear or high levels of physical activity. Odor mitigation through fiber selection alone is therefore insufficient for underwear applications. Effective odor management requires a multifunctional strategy that not only inhibits microbial growth but also addresses the sensory perception of freshness. This requirement has driven growing interest in fragrance-integrated textiles, where controlled aroma release complements antimicrobial mechanisms to enhance both physiological hygiene and psychological comforts [20].

**5. Fragrance Technologies for Textile Applications: Principles and Performance**

Fragrance integration into textiles has evolved significantly over the past two decades, transitioning from simple surface-applied perfumes to advanced controlled-release systems designed for durability, skin compatibility, and sustained performance. For underwear applications, fragrance technologies must satisfy particularly stringent requirements, including resistance to repeated laundering, minimal skin irritation, controlled release under body movement and heat, and compatibility with soft, breathable textile structures. Among the available approaches, microencapsulation, cyclodextrin-based inclusion systems, and essential oil finishes have emerged as the most relevant technologies for functional underwear [21].

Microencapsulation is currently regarded as the most advanced fragrance delivery technique in textile engineering. In this approach, fragrance oils are enclosed within microscopic capsules composed of polymeric or biopolymeric shell materials such as melamine–formaldehyde resins, polyurethane, gelatin, gum arabic, or chitosan. These capsules typically range from one to several tens of micrometers in diameter and are affixed to the fabric surface using suitable binders. Encapsulation protects the fragrance from premature evaporation, oxidation, and degradation during storage and laundering, ensuring prolonged sensory performances [22].

The release of fragrance from microcapsules occurs through mechanical and thermal stimuli generated during wear. Friction between fabric and skin, body movement, and localized temperature increases cause gradual rupture or diffusion through the capsule shell, enabling controlled fragrance emission over extended periods. This mechanism is particularly advantageous for underwear, where continuous motion and skin contact allow sustained aroma release throughout daily wear. When optimized correctly, microencapsulated fragrances can remain effective for several dozen washing cycles without significantly altering fabric softness or breathability [23].

Cyclodextrin-based fragrance systems offer an alternative approach that relies on molecular host–guest interactions rather than physical encapsulation. Cyclodextrins are cyclic oligosaccharides derived from starch, characterized by a hydrophilic exterior and a hydrophobic internal cavity capable of hosting fragrance molecules. When applied to textile surfaces, cyclodextrins form inclusion complexes with volatile fragrance compounds, reducing their evaporation rate and enabling gradual release in response to humidity and temperature changes. Unlike microcapsules, cyclodextrins do not rely on shell rupture, which allows them to maintain fabric flexibility and softness—an important consideration for intimate apparels [24]. Cyclodextrin-treated textiles also exhibit excellent wash durability and, in some cases, the ability to reabsorb fragrance during laundering when fragrance-containing detergents are used. Their high biocompatibility and low risk of skin irritation make cyclodextrins particularly suitable for daily-use bamboo–hemp underwear designed for prolonged skin contact.

Essential oil finishes represent the most natural and traditionally appealing method of fragrance integration. In this approach, plant-derived oils such as lavender, tea tree, peppermint, lemongrass, rose, and eucalyptus are applied directly to the fabric surface through padding, spraying, or exhaustion techniques. In addition to providing fragrance, many essential oils possess intrinsic antimicrobial, antifungal, and anti-inflammatory properties, which can further enhance hygiene and wearer comfort.

However, essential oil finishes suffer from inherent limitations related to volatility and wash durability. Without molecular fixation or encapsulation, essential oils tend to evaporate rapidly and lose effectiveness after only a limited number of laundering cycles. Furthermore, direct application at high concentrations may increase the risk of skin sensitivity. Consequently,

essential oil finishes are most effective when used in combination with microencapsulation or cyclodextrin systems, which improve fragrance retention while maintaining skin safety [25].

**6. Compatibility of Fragrance Systems with Bamboo–Hemp Underwear**

The successful integration of fragrance technologies into bamboo–hemp underwear depends strongly on the physicochemical compatibility between fragrance systems and natural fiber substrates. Bamboo and hemp fibers are rich in hydroxyl functional groups, which promote strong interactions with binders, encapsulation matrices, and cyclodextrin molecules [26]. This intrinsic surface chemistry enhances fragrance fixation compared to hydrophobic synthetic fibers, allowing effective fragrance retention with relatively low chemical add-on levels. Knitted fabric structures commonly used in underwear, such as single jersey, rib, and interlock knits, provide high surface area and structural flexibility that favor fragrance adhesion and release. However, these structures are also subjected to repeated stretching, compression, and abrasion during wear and laundering. As a result, fragrance delivery systems must be mechanically robust and securely bonded to the fiber surface to avoid premature loss. Optimization of binder composition and application parameters is therefore critical to balancing fragrance durability with fabric softness, air permeability, and moisture management [27].

Excessive application of binders or fragrance carriers can impair breathability and negatively affect tactile comfort, while insufficient fixation leads to rapid fragrance depletion. Bamboo–hemp systems offer a unique advantage in this regard, as their natural affinity for bio-based finishes allows effective fragrance integration with minimal compromise to comfort. When properly engineered, fragrance-integrated bamboo–hemp underwear can achieve sustained aroma release while preserving the essential properties required for intimate apparels [28, 29].

**7. Synthesis of Fragrance Strategies for Functional Underwear**

Collectively, microencapsulation, cyclodextrin inclusion, and essential oil finishing should be viewed as complementary rather than competing strategies in the development of fragrant bamboo–hemp underwear. Microencapsulation provides the highest level of fragrance longevity, cyclodextrins ensure softness and reusability, and essential oils contribute natural therapeutic benefits. Strategic combination of these technologies enables the development of multifunctional underwear capable of delivering long-lasting freshness, enhanced hygiene, and improved psychological comfort, thereby meeting the evolving demands of sustainable wellness textiles [30].

**8. Dual-Actions Odor Control and Antimicrobial Enhancement in Bamboo–Hemp Underwear**

While fragrance integration plays a crucial role in improving sensory freshness and wearer confidence, fragrance alone is insufficient to address the root causes of odor formation in underwear. Long-lasting odor management requires a dual-action approach that combines controlled fragrance release with effective antimicrobial strategies capable of suppressing odor-causing microorganisms. Bamboo and hemp fibers provide a favorable foundation for such systems due to their inherent antimicrobial properties; however, their effectiveness can be significantly enhanced through the application of functional antimicrobial finishes. The synergistic integration of antimicrobial agents with fragrance delivery technologies enables sustained freshness by simultaneously preventing odor formation and improving odor perceptions [8, 31].

Among various antimicrobial agents explored for textile applications, zinc oxide has attracted considerable attention due to its broad-spectrum antimicrobial activity, chemical stability, and skin compatibility. Zinc oxide inhibits bacterial growth through multiple mechanisms, including the generation of reactive oxygen species, disruption of bacterial cell membranes, and

interference with intracellular metabolic processes. When applied to bamboo–hemp underwear, zinc oxide effectively suppresses the proliferation of odor-causing bacteria, thereby reducing the biochemical degradation of sweat components. In addition to antimicrobial action, zinc oxide provides ultraviolet protection and contributes to fabric durability, making it particularly attractive for multifunctional underwear applications. Importantly, zinc oxide exhibits strong compatibility with fragrance systems, as it does not interfere with aroma release and can enhance the overall freshness perception by minimizing background odor formation.

Chitosan represents another promising antimicrobial finish for bamboo–hemp underwear, particularly within the context of sustainable and bio-based textile processing. Derived from chitin, chitosan possesses inherent antibacterial activity due to its polycationic nature, which enables electrostatic interaction with negatively charged bacterial cell membranes. This interaction disrupts membrane integrity and inhibits microbial growth. Chitosan also exhibits excellent film-forming properties and strong affinity for natural fibers, allowing it to act simultaneously as an antimicrobial agent and a binding medium for fragrance microcapsules. When used in fragrance-integrated underwear, chitosan enhances capsule adhesion, improves wash durability, and maintains fabric softness. Its hypoallergenic nature further supports its suitability for intimate apparel intended for prolonged skin contacts [32].

More recently, probiotic finishes have emerged as an advanced and biologically inspired approach to odor control in textiles. Unlike conventional antimicrobial treatments that aim to eliminate microorganisms indiscriminately, probiotic systems introduce beneficial bacteria onto the fabric surface. These microorganisms compete with odor-causing bacteria for nutrients and space, effectively suppressing the growth of malodor-producing species. In bamboo–hemp underwear, probiotic finishes offer long-term freshness by establishing a stable microbial balance rather than relying solely on chemical inhibition. When combined with fragrance delivery systems, probiotics contribute to sustained odor suppression while fragrance release enhances the sensory experience, creating a holistic freshness management strategy [33].

The integration of antimicrobial finishes with fragrance microencapsulation or cyclodextrin systems results in a synergistic dual-action performance. Antimicrobial agents reduce the formation of unpleasant odor compounds at the source, while fragrance systems provide controlled aroma release to maintain perceived freshness throughout wear. This synergy is particularly important for underwear, where high moisture levels and continuous skin contact demand both preventive and sensory solutions. The effectiveness of such dual-action systems depends on careful formulation and application to ensure that antimicrobial agents do not compromise fragrance stability or fabric comforts [34, 35].

**9. Role of Fabric Structures in Fragrance Retention and Comfort Performance**

In addition to fiber composition and chemical finishes, fabric structure plays a critical role in determining the performance of fragrance-integrated bamboo–hemp underwear. Knitted fabrics are predominantly used in intimate apparel due to their elasticity, softness, and ability to conform to body contours. The structural characteristics of knitted fabrics influence surface area, air permeability, moisture management, and mechanical durability, all of which affect fragrance retention and release behavior.

Single jersey fabrics are widely used for lightweight and everyday underwear applications. Their relatively open structure and smooth surface facilitate efficient moisture transport and breathability, contributing to wearer comfort. In fragrance-integrated systems, single jersey fabrics allow effective adhesion of fragrance microcapsules and cyclodextrin finishes due to their high surface accessibility. However, their lower fabric density may result in moderate

fragrance retention compared to more compact structures, particularly under repeated laundering [36]. Rib-knit structures, such as one-by-one or two-by-two rib, offer enhanced elasticity and recovery, making them ideal for body-conforming underwear. The alternating knit and purl loops create a textured surface with increased surface area, which can improve the mechanical anchoring of fragrance carriers. This structural complexity enhances fragrance retention while maintaining flexibility and softness. Rib fabrics also provide improved air circulation, which supports moisture evaporation and contributes to a balanced microclimate between fabric and skin.

Interlock fabrics represent a more compact and stable knitted structure, characterized by a smooth surface on both sides and higher fabric density. Interlock knits exhibit superior softness, thermal insulation, and dimensional stability, making them suitable for premium or seasonal underwear. Their dense structure allows greater retention of fragrance delivery systems and antimicrobial finishes, resulting in prolonged functional performance. However, excessive add-on levels must be avoided to preserve breathability and prevent stiffness [37, 38].

The mechanical deformation experienced by underwear during wear, including stretching, compression, and friction, has a direct influence on fragrance release behavior. In microencapsulated systems, these mechanical actions trigger capsule rupture, enabling controlled aroma diffusion. Fabric structures that undergo frequent deformation, such as rib and interlock knits, can therefore enhance fragrance activation without compromising durability when properly engineered. Optimizing fabric structure alongside fragrance and antimicrobial treatments is essential for achieving consistent performance and long-term comforts [5].

**10. Wash Durability, Comforts Preservation, and Skin Compatibility**

Wash durability represents a critical performance criterion for fragrance-integrated bamboo–hemp underwear, as intimate garments are subjected to frequent laundering. Fragrance delivery systems and antimicrobial finishes must remain effective over multiple wash cycles while preserving essential comfort properties such as softness, elasticity, air permeability, and moisture management. Poorly designed finishes may lead to rapid loss of functionality, fabric stiffening, or skin irritation, undermining consumer acceptance [39].

Microencapsulated fragrance systems generally demonstrate superior wash durability compared to direct essential oil finishes, with fragrance retention reported over several dozen laundering cycles under optimized conditions. Cyclodextrin-based systems also exhibit excellent resistance to washing due to their molecular bonding mechanisms and can, in some cases, be reactivated through fragrance reloading during laundering. Antimicrobial finishes such as zinc oxide and chitosan show varying degrees of durability depending on particle size, bonding method, and textile structure, highlighting the importance of formulation optimization. Skin compatibility is particularly critical for underwear applications. Fragrance systems must be carefully selected to avoid allergenic compounds, excessive volatility, or direct skin exposure to concentrated oils. Encapsulation and molecular inclusion strategies significantly reduce the risk of skin irritation by controlling fragrance release and minimizing direct contact. Bio-based antimicrobial agents such as chitosan and probiotics further enhance skin safety, aligning with consumer demand for gentle and natural textile solutions [40].

**11. Implications for Sustainable Wellness Underwear Design**

The integration of dual-action odor control systems with fragrance delivery technologies in bamboo–hemp underwear represents a significant advancement in the design of sustainable wellness textiles. By addressing both the biochemical causes of odor formation and the sensory

dimensions of freshness, these systems provide comprehensive comfort and hygiene solutions tailored to intimate apparel. The use of natural fibers and bio-compatible finishes further supports environmental sustainability and skin health, positioning fragrance-integrated bamboo–hemp underwear as a viable alternative to synthetic performance garments [41].

**12. Sensory Comfort, Aromatherapeutic Effects, and Psychological Well-Being**

Beyond physical comfort and hygiene, fragrance-integrated bamboo–hemp underwear contributes to sensory and psychological well-being, which is increasingly recognized as a key dimension of wellness textiles. Fragrances have long been associated with emotional regulation and stress management through aromatherapeutic pathways. When released gradually from textile substrates, fragrances interact with the olfactory system in a subtle and sustained manner, influencing mood and perceived comfort without overwhelming sensory stimulation. This is particularly relevant for underwear, which remains in continuous contact with the body and can serve as a constant source of low-intensity sensory feedbacks [3].

Fragrances such as lavender, chamomile, and sandalwood are widely associated with relaxation, anxiety reduction, and improved sleep quality, making them suitable for nightwear and meditation-oriented underwear. Citrus-based fragrances, including lemon, orange, and bergamot, provide refreshing and energizing effects that are well suited for sportswear and summer underwear. Peppermint and eucalyptus impart cooling sensations that enhance thermal comfort during physical activity, while rose and vanilla contribute to a perception of luxury and emotional warmth in premium underwear categories. Controlled-release technologies ensure that these fragrances are delivered gradually, preventing rapid sensory fatigue and maintaining a consistent level of comfort throughout the wear cycle [42].

The psychological perception of freshness also plays a critical role in wearer confidence and overall satisfaction. Even when microbial growth is effectively controlled, the presence of a pleasant fragrance reinforces the perception of cleanliness and hygiene. This sensory reassurance is particularly important in intimate apparel, where discomfort or self-consciousness related to odor can negatively affect well-being. By combining odor prevention with controlled fragrance release, bamboo–hemp underwear addresses both physiological and psychological dimensions of comfort, reinforcing its role as a wellness-enhancing garment rather than merely a functional products [43, 44].

**13. Safety, Skin Compatibility, and Regulatory Considerations**

Safety and skin compatibility are paramount in the development of fragrance-integrated underwear, given the prolonged and intimate contact with sensitive skin areas. Any functional finish applied to underwear must meet stringent safety requirements to avoid irritation, sensitization, or allergic reactions. Fragrance compounds, in particular, must be carefully selected and formulated to minimize potential adverse effects. Direct application of concentrated fragrance oils onto textile surfaces is generally unsuitable for intimate apparel due to the risk of skin irritation and rapid volatilization [45].

Controlled-release systems such as microencapsulation and cyclodextrin inclusion significantly enhance skin safety by limiting direct skin exposure to fragrance compounds. Encapsulation isolates fragrance oils within protective shells, releasing them gradually in response to mechanical and thermal stimuli. Cyclodextrin-based systems further reduce irritation risk by hosting fragrance molecules within molecular cavities, ensuring slow and reversible release. These approaches not only improve durability but also align with regulatory guidelines governing cosmetic and textile products [46, 47].

Antimicrobial finishes must also comply with regulatory standards related to biocompatibility and environmental impact. Zinc oxide is widely regarded as safe for textile applications and is

already used in cosmetic and medical products. Chitosan, being bio-based and biodegradable, offers excellent skin compatibility and low toxicity. Probiotic finishes represent an emerging area where regulatory frameworks are still evolving; however, their biological mode of action and non-toxic nature suggest strong potential for safe application in textiles. Compliance with international standards such as OEKO-TEX®, REACH, and relevant ISO and AATCC testing protocols is essential for ensuring consumer safety and facilitating market acceptances [46].

**14. Applications and Market Potentials of Fragrance-Integrated Bamboo–Hemp Underwear**

The multifunctional performance of fragrance-integrated bamboo–hemp underwear positions it for a wide range of applications across both functional and premium apparel markets. In sports and activewear, the combination of moisture management, antimicrobial activity, and controlled fragrance release addresses the challenges associated with intense perspiration and prolonged wear. For daily underwear, these textiles provide sustained freshness, comfort, and skin-friendly performance, enhancing user satisfaction during routine activities [48].

Fragrance-integrated bamboo–hemp underwear is also highly relevant for travel wear, where access to frequent laundering may be limited and prolonged freshness is particularly valuable. In wellness-focused categories such as yoga, meditation, and sleepwear, the incorporation of calming fragrances adds an additional dimension of relaxation and psychological comfort. Maternity and sensitive-skin underwear represent another promising application area, where natural fibers, gentle antimicrobial finishes, and controlled fragrance release can offer improved comfort and hygiene without compromising safety.

From a commercial perspective, increasing consumer demand for sustainable, eco-friendly, and wellness-oriented apparel supports strong market potential for bamboo–hemp underwear. Brands seeking differentiation in a competitive market can leverage the combination of natural fibers, fragrance technology, and odor control to create high-value products that align with sustainability goals and consumer expectations. As awareness of aromatherapy and holistic well-being continues to grow, fragrance-integrated underwear is likely to gain broader acceptance in both mass-market and luxury segments [48].

**15. Challenges, Research Gaps, and Future Directions**

Despite significant progress in fragrance-integrated textile technologies, several challenges remain in the development and commercialization of bamboo–hemp underwear. One key challenge lies in optimizing the balance between fragrance durability and fabric comfort. Excessive application of binders or functional finishes can impair breathability, softness, and elasticity, while insufficient fixation leads to rapid loss of fragrance and antimicrobial effectiveness. Advanced formulation strategies and fiber–finish interaction studies are needed to address this trade-off more effectively [49].

Another critical research gap concerns the long-term interaction between fragrance systems and antimicrobial agents. While synergistic effects have been demonstrated in short-term studies, the stability of these systems under repeated laundering and extended wear requires further investigation. In particular, the interaction between probiotic finishes and fragrance delivery systems remains largely unexplored and represents a promising avenue for future research. Understanding how beneficial microorganisms coexist with fragrance compounds and encapsulation matrices could lead to innovative bio-responsive textile systems [50].

Sustainability assessment represents another important area for future investigation. While bamboo and hemp fibers are widely regarded as environmentally friendly, comprehensive life cycle assessments of fragrance-integrated underwear are limited. Future studies should evaluate the environmental impact of fragrance carriers, binders, and antimicrobial agents alongside fiber production and garment manufacturing. The development of fully bio-based

encapsulation systems and biodegradable fragrance carriers would further enhance the sustainability profile of these textiles [51, 52].

Emerging technologies such as stimuli-responsive capsules, moisture-activated fragrance release, and smart textiles capable of adapting aroma intensity to environmental conditions offer exciting opportunities for next-generation underwear design. Integration with wearable sensors and responsive materials could enable dynamic fragrance release tailored to wearer activity, temperature, or stress levels. Such innovations would further strengthen the role of underwear as an interactive wellness platform rather than a passive garment.

**16. Conclusion**

This review has provided a comprehensive and critical analysis of fragrance-integrated bamboo–hemp underwear as an emerging category of sustainable wellness textiles. By examining the fundamental mechanisms of odor formation, the intrinsic properties of bamboo and hemp fibers, and the performance of advanced fragrance delivery technologies, the review highlights the potential of natural fiber-based systems to address longstanding challenges in intimate apparel. The integration of controlled fragrance release with antimicrobial enhancement represents a dual-action strategy that simultaneously prevents odor formation and enhances sensory freshness, contributing to both physical hygiene and psychological comfort. Bamboo–hemp fiber blends offer a unique combination of softness, breathability, durability, and inherent antimicrobial behavior, making them particularly suitable for next-to-skin applications. When combined with microencapsulation, cyclodextrin inclusion, or essential oil finishes, these fibers enable sustained fragrance release without compromising comfort or skin safety. The incorporation of antimicrobial agents such as zinc oxide, chitosan, and probiotics further enhances odor control and durability, positioning fragrance-integrated bamboo–hemp underwear as a high-performance yet sustainable alternative to synthetic garments.

Despite remaining challenges related to durability optimization, regulatory compliance, and sustainability assessment, the convergence of natural fibers, fragrance technology, and antimicrobial systems offers a compelling pathway for the development of next-generation functional underwear. This review establishes a foundational framework for future research and industrial innovation, demonstrating that fragrance-integrated bamboo–hemp underwear represents not only a viable commercial product but also a meaningful advancement in the broader field of sustainable wellness textiles.

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