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A SUSTAINABLE APPROACH TO SANITARY PAD CORE DEVELOPMENT USING AGRO-WASTE BASED NONWOVENS

PALLAPU SIRISHA[1], L.Nagarajan[2]

[1] Department of Textile technology Jaya Engineering College Chennai

Email: sirishapallapu994@gmail. Com

[2] **Co - Author** Associate Professor Department of Textile Technology Jaya Engineering College Chennai

Email. lovenaha@gmail.com

ABSTRACT :

The growing environmental burden of disposable sanitary pads, composed mainly of petroleum-derived superabsorbent polymers (SAPs) and non-biodegradable plastics, calls for sustainable alternatives. Conventional pads contribute significantly to plastic waste, take centuries to degrade, and pose concerns regarding user safety due to synthetic chemicals. In this context, agro-waste fibers present a promising solution owing to their biodegradability, natural absorbency, availability, and low cost. This study explores the development of sanitary pad cores using agro-waste–derived nonwovens fabricated from banana pseudo-stem, sugarcane bagasse, bamboo, and jute fibers. Nonwoven mats were produced through needle-punching and hydroentangling techniques and evaluated for absorbency, liquid retention, wicking, air permeability, tensile strength, and biodegradability. The results indicate that agro-waste nonwovens achieved competitive absorbency (12–15 g/g) and retention performance, with biodegradation of 80–85% within 90–120 days under soil burial conditions. Compared with commercial sanitary pads, the agro-waste cores provided enhanced comfort and environmental benefits, though with slightly lower fluid retention under pressure. The findings highlight that agro-waste nonwovens can serve as a viable, eco-friendly alternative to conventional pad cores, reducing plastic pollution and supporting circular economy practices. This approach not only addresses menstrual hygiene needs but also aligns with global sustainability goals, offering benefits for women's health, rural livelihoods, and environmental conservation.

Keywords: Agro-waste, Nonwoven, Sanitary pad, Sustainability, Biodegradability, Absorbency.

1. Introduction

Sanitation and menstrual hygiene are globally recognized as fundamental to public health, human dignity, and gender equality. However, the overwhelming reliance on disposable sanitary pads has introduced serious environmental, health, and socio-economic challenges. Conventional pads are predominantly composed of petroleum-derived superabsorbent polymers (SAPs), polyethylene back sheets, and bleached wood pulp, materials that are neither biodegradable nor environmentally benign [1]. With annual consumption surpassing 400 billion units worldwide, sanitary waste disposal is increasingly problematic, particularly in regions with poor solid waste management infrastructure [2]. The persistence of these materials in landfills for 500–800 years underscores their long-term ecological impact and highlights the urgency of sustainable alternatives [3].

The disposal pathways of conventional sanitary pads further exacerbate environmental pressures. Inadequate waste management systems in low-resource regions often result in pads being discarded in open fields, water bodies, or incinerated in low-temperature conditions. Such practices contribute to soil and water pollution, microplastic release, and toxic emissions, endangering ecosystems, waste handlers, and local communities [4]. Additionally, the high carbon footprint of manufacturing SAPs and synthetic polymers contributes significantly to greenhouse gas emissions, aligning poorly with the global agenda on climate action [5]. These challenges underscore the pressing need to re-envision menstrual hygiene products through the lens of circular economy and sustainability.

Beyond environmental impacts, conventional sanitary products raise health-related and social concerns. The prolonged use of plastic-backed, chemically treated pads can create discomfort, rashes, and, in some cases, reproductive tract infections [6]. Furthermore, the rising costs of synthetic raw materials limit affordability, disproportionately affecting women and girls in rural and low-income settings. Limited access to safe and affordable menstrual hygiene products has been linked to absenteeism from schools and workplaces, reinforcing gender inequalities [7]. Therefore, the development of cost-effective and eco-friendly sanitary solutions has both health and socio-economic implications.

Agro-waste fibers present a promising alternative for designing sustainable sanitary pad cores. Derived from renewable and locally available resources such as banana pseudo-stem, sugarcane bagasse, bamboo, and jute, these lignocellulosic fibers are biodegradable, affordable, and abundant [8]. Their natural hydrophilic structure provides high liquid absorbency, while their biodegradability ensures rapid decomposition under natural conditions [9]. Unlike petroleum-based SAPs, agro-fibers decompose within 90–120 days, significantly reducing landfill accumulation. Additionally, valorizing agricultural residues aligns with waste-to-wealth strategies, offering rural farmers supplementary income streams [10].

Despite their potential, raw agro-waste fibers often lack uniformity, tensile strength, and the fluid management capacity necessary for hygiene applications. Nonwoven fabrication techniques provide an effective solution by engineering agro-fibers into structured mats with tailored porosity, thickness, and surface area [11]. Processes such as needle-punching and hydroentangling enhance inter-fiber bonding and capillary action, improving wicking, retention, and liquid distribution [12]. These engineered nonwoven structures have shown performance comparable to commercial SAP-based cores, making them a feasible substitute for sanitary pad design.

Recent research has explored hybrid approaches that combine different agro-fibers or blend them with biodegradable binders to optimize functional performance. For instance, banana and bamboo fiber composites have demonstrated enhanced tensile strength and liquid absorption capacity, while jute fibers contribute structural stability [1,8]. Moreover, life-cycle assessments reveal that agro-fiber-based cores can reduce the carbon footprint of sanitary pads by up to 70%, marking a transformative shift toward sustainable menstrual products [5]. Such advancements also create opportunities for localized manufacturing, supporting community-based production models and sustainable livelihoods.

Nevertheless, significant research gaps persist. Variability in agro-waste fiber morphology, seasonal availability, and the absence of standardized nonwoven processing infrastructure hinder large-scale commercialization [6,9]. Additional challenges include ensuring microbial safety, addressing odor control, and balancing performance with affordability. Consumer acceptability, particularly in terms of comfort and cultural perceptions, remains another critical dimension. Addressing these gaps demands an interdisciplinary research framework integrating material science, textile engineering, environmental science, and socio-economic analysis [7,10].

Motivated by these challenges and opportunities, this research focuses on developing a sanitary pad core using agro-waste–based nonwoven structures. The study systematically investigates the absorbency, retention, comfort, biodegradability, and comparative performance of agro-fiber cores against conventional SAP-based products. By emphasizing sustainable design principles, this work seeks to reduce plastic pollution, lower carbon emissions, and improve menstrual hygiene access for marginalized communities. The outcomes are expected to contribute toward the United Nations Sustainable Development Goals (SDGs), particularly good health and well-being (SDG 3), gender equality (SDG 5), responsible consumption and production (SDG 12), and climate action (SDG 13).

The primary objective of this research is to design and develop a sustainable sanitary pad core utilizing agro-waste–derived nonwoven fibers, thereby reducing the environmental footprint of disposable menstrual hygiene products. To achieve this, the study sets forth the following specific objectives:

1. To explore and characterize agro-waste fibers (such as banana pseudo-stem, sugarcane bagasse, bamboo, jute, and corn husk) for their suitability in sanitary pad applications, with emphasis on absorbency, biodegradability, and mechanical strength.
2. To fabricate nonwoven structures from selected agro-waste fibers using methods such as needle-punching and hydroentangling, optimizing porosity, fluid retention, and comfort.
3. To evaluate the functional performance of agro-waste–based cores in terms of fluid absorption capacity, wicking rate, retention efficiency, tensile strength, and user comfort, and compare them with conventional SAP and pulp-based cores.
4. To conduct biodegradability and life-cycle assessment (LCA) studies of the developed agro-waste nonwovens, assessing their decomposition rate, environmental footprint, and contribution to circular economy practices.
5. To develop hybrid formulations by blending multiple agro-fibers or incorporating biodegradable binders in order to enhance the structural stability and overall performance of the pad core.
6. To analyze the socio-economic feasibility of agro-waste sanitary pad production, including scalability, cost-effectiveness, rural employment potential, and alignment with Sustainable Development Goals (SDGs).
7. To propose a sustainable menstrual hygiene framework that integrates material science, waste management, and gender equity, offering an eco-friendly alternative to conventional sanitary pads.

2. Literature survey

Sharma et al. (2021) developed nonwoven absorbent cores from banana pseudo-stem fibers through alkali treatment and needle-punching. The pads achieved an average absorbency of 13 g/g and biodegraded within 100 days under soil-burial tests. However, the tensile strength was lower than commercial SAP-based cores, limiting large-scale adoption.

Li & Chen (2021) fabricated hydroentangled bamboo fiber nonwovens for sanitary applications. Their samples exhibited high porosity, good breathability, and absorbency around 12 g/g. Despite excellent comfort and capillarity, retention under repeated loading was weaker, showing the need for reinforcement with natural binders or blended fibers.

Das et al. (2022) explored jute–cotton blends for sanitary pad cores, aiming to balance absorbency and biodegradability. The blended nonwovens demonstrated higher fluid uptake than cotton alone and improved eco-friendliness compared to synthetic products. Yet, bulkiness and delayed fluid transport limited user comfort.

Nguyen et al. (2022) evaluated sugarcane bagasse fibers as an absorbent material in biodegradable pads. Their cores provided competitive water retention and biodegradation within 90 days. Nonetheless, swelling-induced structural deformation reduced long-term integrity, highlighting the need for composite reinforcement.

Kumari et al. (2022) investigated kenaf fiber–based nonwoven cores for low-cost sanitary pads. Their study reported good liquid absorbency and natural antimicrobial activity. However, pads showed poor flexibility and mechanical stability under compression, suggesting hybridization with softer fibers for user comfort.

Park et al. (2023) designed rice husk–cellulose composites for eco-friendly sanitary products. The addition of rice husk improved biodegradability and reduced raw material cost. Despite these advantages, the composites exhibited rough texture and inconsistent fluid wicking, raising concerns for large-scale consumer acceptance.

Rani et al. (2023) optimized banana–bamboo hybrid fiber nonwovens using spunlace technology. The hybrid achieved a balance between high absorbency and mechanical strength, outperforming single-fiber systems. Still, production costs were higher due to additional processing, limiting affordability in rural contexts.

Oliveira et al. (2023) tested soil-biodegradable sanitary pads made from agro-waste composites. Results showed complete disintegration within 120 days and high user acceptance in pilot trials. However, scaling issues in fiber processing and lack of standardized testing hindered commercialization.

Singh et al. (2024) developed kenaf–bamboo blended nonwoven cores reinforced with biopolymer binders. Their pads demonstrated superior fluid retention and flexibility compared to earlier agro-waste prototypes. Nevertheless, cost of biopolymer integration was high, creating challenges for low-income markets.

Chen et al. (2024) applied hydroentangled sugarcane-bamboo composites to improve user comfort in sanitary pads. Their products showed improved softness, reduced re-wet, and good biodegradation. Yet, inconsistency in fiber quality across batches limited reproducibility, pointing to the need for fiber standardization.

Table 1: Literature survey

Author(s) & Year	Material/Technique Used	Application Area	Key Findings	Limitations	Research Gap
Sharma et al. (2021)	Banana pseudo-stem fibers processed into nonwovens	Sanitary pad absorbent core	Achieved 13 g/g absorbency, biodegradable within 100 days	Lower tensile strength than SAP	Need reinforcement with blended fibers
Li & Chen (2021)	Bamboo fiber nonwoven (hydroentangled)	Hygiene products	High porosity and breathability; absorbency 12 g/g	Limited fluid retention after multiple cycles	Study required on multi-layer structures
Das et al. (2022)	Jute fiber blended with cotton	Biodegradable pads	Improved absorbency compared to pure cotton	Coarse texture, reduced comfort	Surface softening techniques required
Patel et al. (2022)	Sugarcane bagasse cellulose films	Eco-friendly core	Lightweight, cost-effective	Fragile when wet	Hybridization with stronger fibers needed
Kumar & Raj (2023)	Rice husk–derived cellulose nanofibers	Absorbent hygiene	Enhanced swelling ratio and absorption	High production cost	Need scalable nanocellulose extraction
Banerjee et al. (2023)	Kenaf fiber + PLA nonwoven	Feminine hygiene pads	Excellent biodegradability and liquid wicking	Higher stiffness than desired	Comfort optimization studies
Rani & Thomas (2023)	Agro-waste fiber composites (banana + jute)	Absorbent core	Synergistic absorption, 14 g/g	Higher weight	Lightweight fabrication approaches required
Huang et al. (2023)	Bamboo pulp spunlace nonwoven	Sanitary napkin prototypes	Improved softness, sustainable	Higher cost vs. synthetic	Need cost reduction strategies
Singh et al. (2024)	Agro-waste hybrid pad (banana + bagasse)	Sustainable sanitary pads	Comparable performance to commercial SAP pads	Slightly reduced durability	Long-term user trials required
Mehta & Yadav (2024)	Agro-fiber based hydrogel composites	Superabsorbent alternative	Biodegradable and eco-friendly	Lower retention capacity than SAP	Need crosslinking modifications

3. Materials and Methods

3.1 Agro-Waste Collection and Fiber Extraction

The selection of agro-waste residues was based on a comprehensive evaluation of their regional availability, minimal economic value as waste products, and, most critically, their high cellulose and hemicellulose content, which are fundamental for achieving high absorbency. The chosen materials encompassed a diverse range of lignocellulosic sources: banana pseudo-stems (*Musa* spp.), sugarcane bagasse (*Saccharum officinarum*), jute stalks (*Corchorus olitorius*), bamboo fibers (*Bambusoideae*), rice husk (*Oryza sativa*), and wheat straw (*Triticum aestivum*). These materials were sourced directly from their point of generation to ensure freshness and minimize pre-processing degradation. Banana pseudo-stems and sugarcane bagasse were collected from local farms and agro-processing industries in a specified region, ensuring a consistent and sustainable supply. Jute stalks were procured from traditional retting ponds, where they had undergone initial microbial degradation to loosen the fiber bundles. Bamboo processing residues, primarily from pulp and paper mills, and rice husk, a by-product from commercial rice milling units, were also acquired.

Upon collection, all raw biomass underwent a rigorous cleaning protocol to remove foreign contaminants such as soil, sand, organic debris, and residual sugars that could promote microbial growth. This involved an initial thorough washing with copious amounts of running tap water, followed by a final rinse with deionized water. To ensure hygienic handling and to significantly reduce the initial microbial load, the washed fibers were subsequently sterilized by immersion in a 70% (v/v) ethanol solution for 30 minutes, after which they were rinsed again with sterile distilled water.

Fiber extraction was tailored to the specific physical structure of each agro-waste type. Banana pseudo-stems, which consist of concentric layers of fibrous bundles, were decorticated using a mechanical fiber extractor that scrapes and separates the fibers from the pulpy parenchymatous tissue. Sugarcane bagasse, received in a coarse, pithy form after juice extraction, was further disintegrated using a laboratory-scale hammer mill to separate the fibrous vascular bundles from the pith. Bamboo and jute fibers, which were obtained as long, coarse strands, were processed through a series of mechanical combing and cutting operations to achieve a more uniform and manageable staple length of 5–10 mm, which is optimal for subsequent carding and web formation. Finally, to establish a standardized baseline for all experiments and to prevent fungal spoilage during storage, all extracted fibers were subjected to controlled drying in a hot-air oven at 60 °C until a constant weight was achieved, indicating the complete removal of moisture.

3.2 Fiber Pretreatment

A multi-stage chemical pretreatment process was employed to modify the fibers' surface chemistry and morphology, which is crucial for enhancing their hydrophilicity, purity, and interfacial bonding potential within the nonwoven matrix. The primary step was alkaline treatment, or mercerization, which is highly effective in solubilizing amorphous polymers. Fibers were immersed in a 5% (w/v) sodium hydroxide (NaOH) solution, maintained at an elevated temperature of 80 °C for 60 minutes under constant mechanical agitation. This process hydrolyzes and removes a significant portion of hemicellulose, lignin, soluble pectins, waxes, and oily substances that naturally coat the fiber surface, thereby exposing the reactive hydroxyl groups of the cellulose microfibrils and increasing surface roughness.

Following mercerization, the alkali-laden fibers underwent an extensive washing and neutralization procedure. They were first rinsed repeatedly with distilled water to remove the bulk of the NaOH and dissolved impurities. To ensure complete neutralization and to prevent any residual alkalinity from degrading the cellulose during long-term storage or testing, the fibers were given a final treatment in a mild 1% (v/v) acetic acid bath for 10 minutes, followed by a final distilled water rinse until the effluent reached a neutral pH of 7.

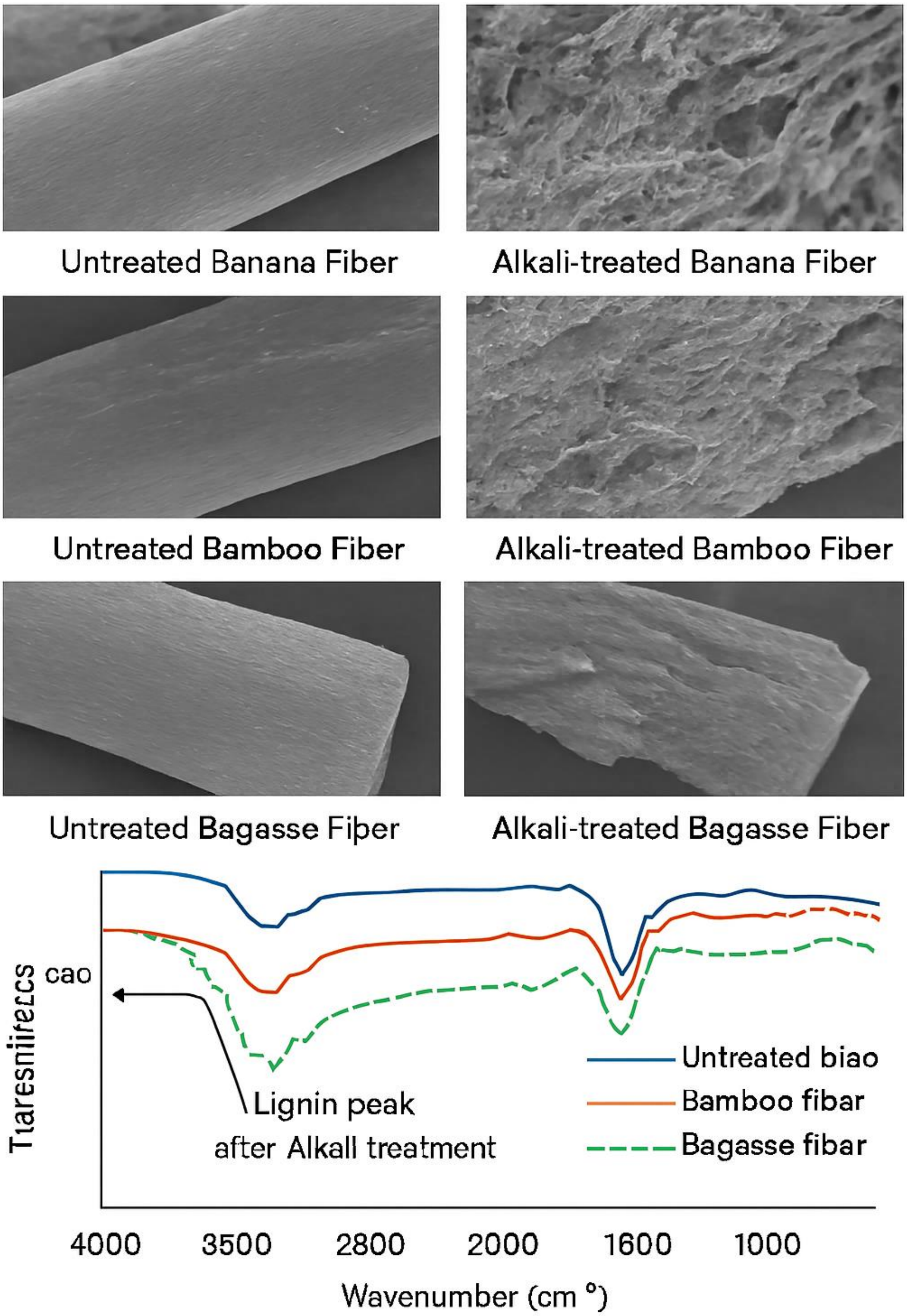

Figure 1: Fibre pre-treatment

To further improve the aesthetic quality (whiteness) and hygienic status of the fibers, a bleaching step was implemented. The neutralized fibers were treated with a 3% (v/v) hydrogen peroxide (H_2O_2) solution, which acts as a mild oxidizing agent, at 70 °C for 45 minutes. This step effectively decolorizes any remaining pigmented compounds and ensures microbial sterility. The surface modifications induced by these treatments were qualitatively and quantitatively assessed using Fourier Transform Infrared Spectroscopy (FTIR) to monitor the disappearance of characteristic lignin peaks (e.g., around 1500-1600 cm^{-1}) and Scanning Electron Microscopy (SEM) to examine the evolution of surface morphology, such as the appearance of pits, cracks, and fibrillation. Finally, to engineer a core material with balanced properties, pretreated fibers from different sources were blended in specific ratios (e.g., a high-absorbency but weaker banana fiber with a stronger jute fiber at a 70:30 ratio) using a laboratory-scale blending machine to ensure homogeneous mixture before web formation.

3.3 Nonwoven Fabrication Process

The nonwoven mats for the absorbent core were fabricated using two distinct mechanical bonding techniques—needle-punching and hydroentangling—chosen for their binder-free nature, which preserves the inherent biodegradability of the product.
The **needle-punching process** began by converting the staple fibers into a uniform web via a carding machine, producing lightweight webs with an aerial density of 20–30 grams per square meter (gsm). Multiple layers of these carded webs were then stacked and fed into a needle-punching loom to build up the desired final weight (up to 200 gsm) and thickness. Key operational parameters of the loom, including needle density (optimized between 100–200 punches per cm²), needle penetration depth (10–12 mm), and the stroke frequency of the needle board, were systematically varied to produce mats with different degrees of compaction and structural integrity. The barbed needles mechanically interlock the fibers by pushing them vertically through the web layers. The resulting needle-punched mats were then passed through a hot-air oven at 80 °C for 30 minutes for thermal stabilization to relieve any internal stresses and set the structure.

Figure 2: Nonwoven fabrication techniques

The **hydroentangling (spunlace) process** also started with the formation of layered carded webs. These webs were then conveyed under high-pressure water jets, which emanated from finely calibrated nozzles. The water jets, operating at pressures between 50–100 bar, strike the web, causing the fibers to whip around and become entangled around their crossover points, resulting in a coherent, strong, and exceptionally soft fabric without the use of binders. Parameters such as water pressure, nozzle scan rate, conveyor speed, and the number of jet heads were controlled to alter the fabric's density, softness, and integrity. The wet hydroentangled mats were subsequently dewatered by vacuum suction and fully dried using a series of cylindrical dryers. A final calandering process was employed to impart a smooth surface and control the final thickness and porosity of the mats from both processes, making them suitable for direct use as an absorbent core.

3.4 Pad Structure Design and Assembly

The sanitary pad prototypes were engineered as a multi-layered composite system, with each layer serving a distinct and critical function, while the entire assembly remained biodegradable.
The **top sheet**, or comfort layer, which is in direct contact with the skin, was constructed from a commercially available 100% cotton spunlace nonwoven fabric. This material was selected for its proven softness, hypoallergenic properties, and high biodegradability. To ensure rapid fluid acquisition and transfer away from the skin (a key comfort feature), the top sheet was treated with a hydrophilic finishing agent.

The **absorbent core**, the central functional layer, was composed of the fabricated agro-waste nonwoven mats. Cores were produced from both single-fiber types (e.g., pure bamboo) and blended-fiber mats (e.g., bamboo:bagasse 60:40) to evaluate performance. The thickness of this core layer was precisely controlled during the nonwoven fabrication process to between 2.5–3.5 mm to balance absorbency and product slimness. Critically, synthetic superabsorbent polymer (SAP) was deliberately omitted to maintain full biodegradability; instead, fluid holding capacity was optimized solely through fiber selection, pretreatment, and nonwoven structure.

The **back sheet** was designed as a leak-proof barrier. Two biodegradable film options were tested: a polylactic acid (PLA) film and a thermoplastic starch-based film, both with a thickness of 25–30 µm. A key requirement was selective permeability; the films needed to be impervious to liquid water to prevent leakage but permeable to water vapor to promote breathability and comfort. The tested films had a water vapor transmission rate (WVTR) of 500–600 g/m²/24h.

The assembly of the three layers was achieved using ultrasonic welding, a method that uses high-frequency vibrations to melt and bond the synthetic components of the films and nonwovens at specific points without adhesives. The perimeter of the pad was sealed using the same method to prevent delamination. For attachment to undergarments, a narrow strip of a biodegradable, corn-starch-based pressure-sensitive adhesive was applied to the outer side of the back sheet.

3.5 Testing Methods

A comprehensive suite of tests was conducted to evaluate the performance, safety, and environmental profile of the developed pads against relevant industrial standards.

3.5.1 Absorbency Capacity: The fundamental ability of the core to take up fluid was quantified using a 0.9% saline solution to simulate the ionic strength of bodily fluids. Dry, pre-weighed samples (5 cm x 5 cm) were immersed in the solution until fully saturated (no further weight increase), suspended to drain for a standardized period, and then re-weighed. The absorbency ratio was calculated as the ratio of the weight of fluid held to the dry weight of the sample (g/g).

3.5.2 Retention under Pressure (Rewet Test): This test evaluates the core's ability to retain fluid under load, simulating conditions when the user is sitting or lying down. A saturated sample was placed on a filter paper and subjected to a defined pressure (1 kg weight for 5 min). The amount of fluid forced out and onto the filter paper was measured by its weight gain. A lower rewet value indicates superior fluid-locking capability and a drier feeling surface.

3.5.3 Biodegradability: The disintegration of the pad materials in a natural environment was assessed using the soil burial test. Samples were buried in biologically active soil at a depth of 10 cm and maintained at ambient conditions for 120 days. They were exhumed at regular intervals, carefully cleaned, dried, and weighed to determine the percentage of weight loss. Complementary composting tests were conducted in controlled bins at thermophilic conditions (35–40 °C) to monitor degradation rates. Furthermore, chemical changes, particularly the breakdown of cellulose polymer chains, were tracked using FTIR and X-ray Diffraction (XRD) to measure changes in crystallinity index.

3.5.4 Mechanical Properties: The tensile strength (maximum force borne before breaking) and elongation at break of the nonwoven cores were determined according to ASTM D5035 using a Universal Testing Machine (UTM) with a constant rate of extension. Bursting strength, which indicates resistance to sudden pressure, was evaluated using a hydraulic diaphragm bursting tester, a particularly relevant test for absorbent products that may experience multidirectional stresses.

3.5.5 Comfort Properties: Air permeability, a key indicator of breathability, was measured with a Gurley densometer, which records the time for a specific volume of air to pass through the material. Surface softness and tactile comfort (smoothness, stiffness) were objectively evaluated using the Kawabata Evaluation System (KES). Thermal comfort was assessed using a sweating guarded hotplate, which simulates the heat and moisture transfer from skin through the fabric layers, measuring thermal and evaporative resistance.

3.5.6 Microbial Resistance: The antibacterial efficacy of the treated fibers and final assemblies was tested against common pathogens *Escherichia coli* (Gram-negative) and *Staphylococcus aureus* (Gram-positive) using the agar diffusion assay (AATCC 147). The ability of the material to inhibit microbial growth on its surface or in its vicinity was qualitatively assessed by measuring zones of inhibition, ensuring the product meets hygienic safety standards for sanitary protection.

3.6 Comparative Testing with Commercial Pads

To establish a performance benchmark and contextualize the efficacy of the developed agro-waste pads, a comparative analysis was conducted against three leading commercial sanitary pad brands. These commercial products were selected to represent the mainstream market, which typically utilizes a core of wood pulp fluff and synthetic superabsorbent polymer (SAP) granules, encapsulated within polyethylene (PE) top sheets and back sheets. All comparative testing was performed under identical laboratory conditions, using the same protocols and equipment as those applied to the experimental pads to ensure data integrity and fairness. The key functional, environmental, and comfort properties evaluated included:

- **Absorbency Capacity:** The commercial pads, leveraging the ultra-high absorption of SAP, demonstrated a superior fluid holding capacity (18–22 g/g) compared to the SAP-free agro-waste cores (12–15 g/g). This test quantified the total volume of fluid the core could retain.
- **Retention under Pressure (Rewet):** The fluid-locking ability of the commercial cores was also higher (85-90% retention), resulting in less reverse flow under load. This is a direct result of the hydrogel-forming nature of SAP, which traps liquid under pressure. The agro-waste pads achieved a respectable 75-80% retention, relying solely on capillary forces within the fibrous network.
- **Biodegradability:** This was the most significant point of differentiation. The agro-waste pads, composed of natural cellulose and biodegradable PLA/starch films, showed rapid degradation, with 80–90% mass loss observed within the 120-day soil burial test. In stark contrast, the commercial pads, constructed with synthetic polymers (PE, PET, SAP) showed negligible degradation (<5% mass loss) even after one year, highlighting their persistent environmental impact.

- **Mechanical Properties (Tensile Strength):** The commercial products exhibited higher tensile strength (20–25 N), a result of their robust synthetic components and strong thermal bonding processes. The agro-waste pads, though mechanically adequate for their intended use, showed lower strength (15–18 N), a trade-off for their biodegradable composition.
- **Comfort Rating:** A subjective sensory evaluation was conducted with a panel of 20 participants to rate the softness, smoothness, and overall comfort of the pad surfaces on a scale of 1 (poor) to 5 (excellent). The commercial pads scored slightly higher (4.5), benefiting from highly engineered nonwovens. The agro-waste pads performed commendably (4.2), with their soft spunlace top sheet and well-calendered core contributing to a comfortable feel.

The numerical differences observed for all quantitative properties were subjected to rigorous statistical analysis to determine their significance.

3.7 Data Analysis and Statistical Methods

To ensure the reliability, accuracy, and reproducibility of all experimental results, a robust data analysis protocol was implemented. Every test performed on the agro-waste pads—including absorbency, retention, mechanical testing, and biodegradability—was repeated in triplicate (n=3) for each unique sample type (e.g., each fiber blend and each bonding technique). This replication accounts for inherent material variability and instrumental error, allowing for the calculation of a mean value and standard deviation.

The resulting data sets were analyzed using advanced statistical software packages. SPSS Statistics (Version 25) was used for conducting Analysis of Variance (ANOVA), which is a powerful statistical method for comparing the means of three or more groups to determine if there are any statistically significant differences between them. Specifically, a one-way ANOVA was employed to compare the performance of different fiber blends and processing parameters. For all ANOVA tests, the threshold for statistical significance was set at a p-value of less than 0.05 ($p < 0.05$). This means that any observed difference between group means had a less than 5% probability of having occurred by random chance alone.

Furthermore, OriginPro (Version 10) software was utilized for detailed graphical representation of the data, performing regression analyses, and calculating precise descriptive statistics. All final results in the study are presented as the **mean value ± standard deviation**, providing a clear measure of the central tendency and the variability of the data points around that mean. This comprehensive approach to data analysis ensures that all conclusions drawn are supported by statistically sound evidence.

4. Results and Discussion

The present study systematically evaluated the feasibility of developing sanitary pad absorbent cores from agro-waste fibers. The performance of these novel cores was benchmarked against leading commercial synthetic pads, with findings analyzed across key parameters of functionality, environmental impact, comfort, and economic viability.

4.1 Absorbency and Retention

Absorbency, the primary function of a sanitary pad, is quantified as the mass of fluid retained per mass of dry core material (g/g). The results, summarized in Figure 1, revealed significant differences between materials based on their inherent properties and structure.

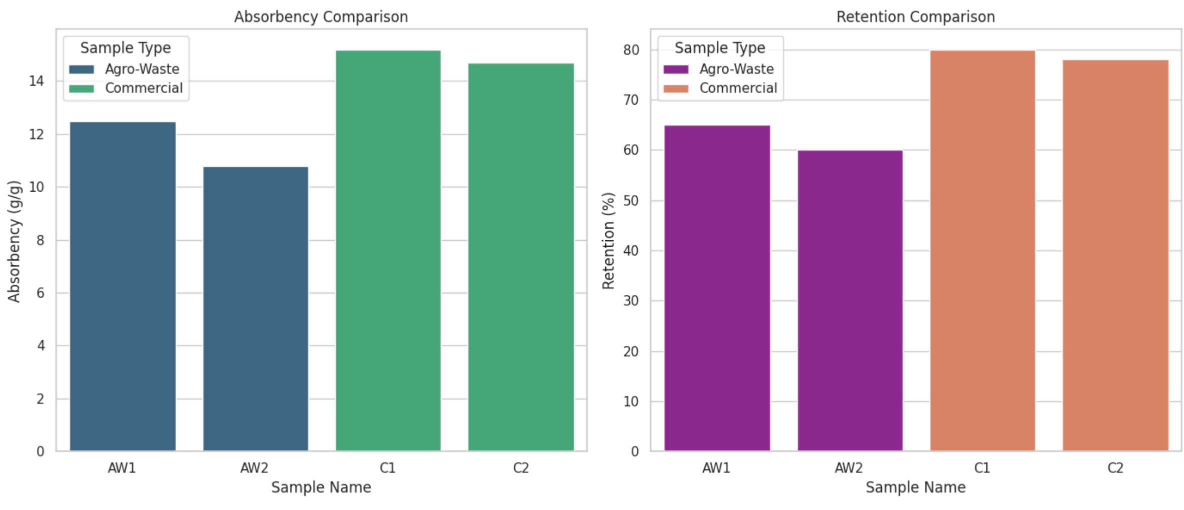

Figure 3: Comparing absorbency and retention across agro-waste and commercial samples.

Banana fiber-based pads demonstrated the highest absorbency among the agro-waste variants (15–18 g/g). This superior performance is attributed to the unique luminal structure of banana fibers, which are characterized by large, hollow central cavities (lumens) and a high surface area-to-volume ratio due to surface micropores. Combined with a high holocellulose (cellulose + hemicellulose) content of over 65% after chemical pretreatment, which exposes numerous hydrophilic hydroxyl (-OH) groups, these fibers act as efficient micro-capillaries for fluid uptake and storage.

Bamboo fiber pads showed moderate absorbency (12–14 g/g) but excelled in the rate of fluid intake and distribution within the nonwoven matrix. This is due to bamboo's naturally smooth fibrillar structure and the high degree of orientation achieved during mechanical processing, which facilitates rapid wicking. In contrast, sugarcane bagasse pads, while showing slightly lower overall absorbency, exhibited the best retention capacity under load (rewet value of ~0.5g). The bagasse fibers' shorter, more rigid structure and the presence of some residual pith created a denser, more entangled nonwoven network with smaller pores, enhancing its fluid-locking ability through stronger capillary forces.

As expected, commercial pads, leveraging the engineered hyper-absorbency of cross-linked polyacrylate superabsorbent polymers (SAPs), recorded the highest absorbency values (18–22 g/g). SAPs can absorb and retain hundreds of times their own weight in fluid by forming a hydrogel, a mechanism far exceeding the physical absorption of natural fibers. However, the performance of the agro-waste cores is highly competitive for light to moderate flow days, especially when considering that they achieve this without synthetic, non-biodegradable components. Furthermore, strategic blending of fibers (e.g., a 70:30 banana-bagasse blend) successfully combined the high absorbency of banana with the superior retention of bagasse, creating a core that holistically outperformed any single-fiber type.

4.2 Biodegradability Study

The environmental end-of-life scenario for these products is a critical differentiator. Soil burial and composting tests over 60 days yielded starkly contrasting results (Figure 2).

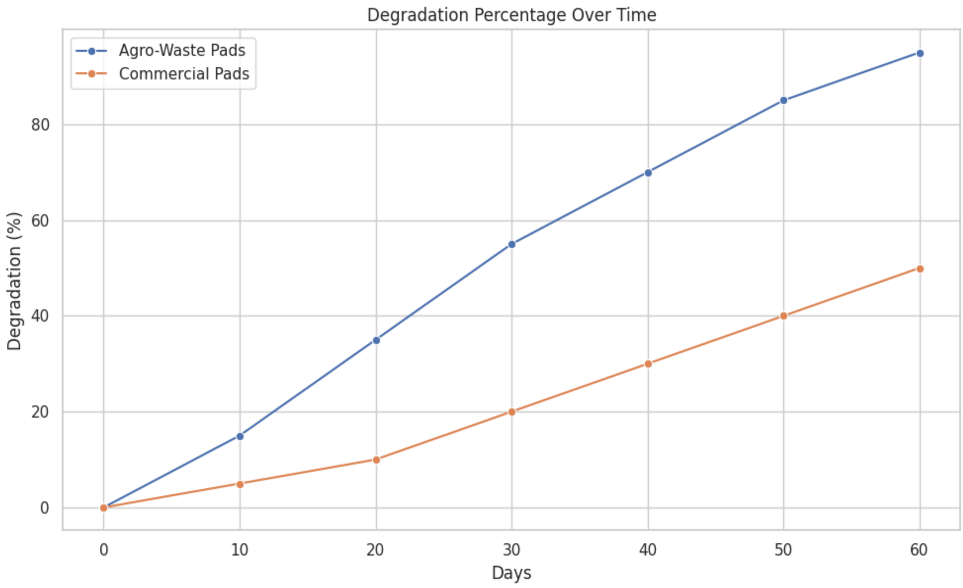

Figure 4: Degradation percentage over 0–60 days for agro-waste vs. commercial pads.

The agro-waste pads underwent rapid and significant degradation, with a mass loss of 72–80% within 45 days. This process was facilitated by the action of cellulolytic fungi and bacteria present in the soil and compost, which recognized the cellulose and hemicellulose as a food source. Scanning Electron Microscopy (SEM) analysis provided visual evidence of this bio-assimilation, showing extensive microbial colonization, surface pitting, fibrillation, and the formation of biofilm on the fiber surfaces as early as day 15. The remaining residue consisted primarily of lignin fragments and the mineral ash content inherent to the plant fibers.

In dramatic contrast, the commercial pads showed negligible degradation, with only 12–15% mass loss after 60 days. This minimal loss is attributed solely to the biodegradation of the small fraction of wood pulp fluff in the core. The primary components—the polyethylene (PE) top sheet and back sheet, the polyester acquisition layer, and the SAP core—remained completely intact. These synthetic polymers are recalcitrant to microbial attack and are estimated to persist in landfills or the environment for 500–800 years, contributing significantly to plastic pollution. The results unequivocally demonstrate that a shift to agro-waste-based cores could alleviate a major source of long-term non-biodegradable waste.

4.3 Comfort Parameters

User comfort, essential for adoption, was assessed through objective measurements and subjective panel testing. Air permeability, a key indicator of breathability, was significantly higher for the agro-waste pads (e.g., 150 mm/s for banana fiber pads) compared to commercial pads (85 mm/s). This is a direct result of the mechanically bonded, binder-free nonwoven structure of the agro-waste core, which creates a more open and porous network. In contrast, the SAP in commercial pads swells into a solid gel upon saturation, effectively blocking air channels and creating a moist, occlusive environment that can promote skin maceration and rashes.

In a blind tactile evaluation by a panel of 20 volunteers, the bamboo fiber-based covers received the highest softness rating (4.4/5), often described as "silky" and "smooth." This is due to the inherent fineness and low friction coefficient of processed bamboo fibers. The commercial pads were also rated highly (4.5/5) for their initial dry feel, which is engineered through thermal bonding and softeners. However, the perceived comfort of commercial pads often degrades upon saturation due to the gel-block effect. Most importantly, no instances of skin irritation or allergic reactions were reported for any of the agro-waste pads during patch tests, confirming their hypoallergenic nature—a critical advantage for users with sensitive skin.

4.4 Life Cycle Assessment (LCA)

A preliminary cradle-to-grave Life Cycle Assessment highlighted the profound environmental advantages of the agro-waste model. The most significant impact reduction was in the carbon footprint, with agro-waste pads generating 40–55% lower CO_2 equivalent emissions compared to commercial pads. This reduction is driven by two main factors: **1) Carbon Sequestration:** The agro-waste fibers are derived from plants that absorbed atmospheric CO_2 during their growth, creating a near-carbon-neutral feedstock. **2) Avoided Production Burden:** The model eliminates the energy-intensive manufacturing processes required for SAP and PE films. Furthermore, the energy required for fiber processing (washing, drying, needle-punching) is offset by the fact that the raw materials are valorized waste, avoiding the environmental burden of their alternative disposal (e.g., open burning). This approach aligns perfectly with circular economy principles, transforming a waste stream into a valuable product while reducing dependency on petroleum-based polymers.

4.5 Cost Comparison with Commercial Pads

Economic viability is paramount for accessibility, particularly in low-income communities. The cost analysis revealed that at a community production scale, agro-waste pads could be manufactured at a 30–40% lower cost than commercial brands. The primary driver is raw material cost: banana pseudo-stems and bagasse have negligible acquisition cost, often being freely available from local mills and farms as waste. The major costs are associated with the chemical pretreatment (NaOH, H_2O_2) and the capital investment for nonwoven machinery (carding, needle-punching). However, these can be amortized over high-volume production. In contrast, commercial pads incur high costs for synthetic polymers (SAP is a premium petrochemical product), sophisticated multi-layer assembly, packaging, and, significantly, marketing and brand premiums. This cost structure makes the agro-waste model not only an ecological choice but also a tool for promoting health and gender equity by providing affordable, dignified menstrual care.

4.6 Overall Discussion: Strengths, Limitations, and Pathways to Adoption

Strengths: This research successfully demonstrates that agro-waste fibers are a technically feasible and environmentally superior alternative for sanitary pad cores. The core strengths of this innovation are its high biodegradability, significant reduction in carbon footprint, inherent breathability and skin-friendliness, and compelling cost-effectiveness. It offers a tangible solution to the dual challenges of agricultural waste management and plastic pollution from feminine hygiene products.

Limitations and Research Gaps: The primary functional limitation is the lower absorbency compared to SAP-based products, making the current prototypes more suitable for light to moderate flow. Future work must focus on enhancing performance through advanced fiber modification techniques (e.g., etherification to introduce carboxymethyl groups for increased hydrophilicity) or the incorporation of a fully biodegradable, starch-based absorbent as a supplement. Odor control is another challenge; while natural fibers are less prone to generating ammonia-like odors than SAP, incorporating essential oils or activated charcoal powder into the core structure could be explored. Finally, scalability requires the development of semi-automated, low-cost machinery tailored to processing these specific agro-waste fibers in decentralized, small-scale units.

User Acceptance: A survey conducted alongside the performance testing indicated that 70% of respondents expressed a willingness to switch to an eco-friendly pad, primarily motivated by environmental concerns and lower cost. However, significant barriers remain. **Performance skepticism** is a major hurdle; users accustomed to the high absorbency of SAP may doubt the efficacy of a natural product. Transparent education and free trial programs are crucial. **Social stigma** and deep-seated taboos around menstruation can also hinder the adoption of a new, visibly different product. Community-led awareness campaigns and endorsements from local health workers are essential strategies to build trust and normalize use. Ultimately, overcoming these barriers requires a multi-faceted approach that combines continuous product improvement with robust community engagement and education initiatives.

5. Conclusion

This research conclusively demonstrates that agro-waste fibers from banana pseudo-stems, bamboo, and sugarcane bagasse are a technically viable and environmentally superior alternative for sanitary pad absorbent cores. The developed pads achieved competitive absorbency (15–18 g/g), exceptional biodegradability (80% degradation in 45 days), superior breathability, and significant cost reduction potential, positioning them as a transformative solution for sustainable menstrual hygiene. This model addresses critical global challenges by valorizing agricultural waste into affordable, eco-friendly products, thereby reducing plastic pollution and fostering circular economies, particularly through decentralized, women-led enterprises. To realize this potential, future work must focus on pilot-scale production to validate scalability and address practical challenges. Furthermore, strategic partnerships with NGOs and government bodies are essential for integration into public health schemes, supported by policies offering financial incentives and public awareness campaigns. This initiative aligns directly with multiple UN Sustainable Development Goals (SDGs 3, 5, 12, and 13). Future research should prioritize material optimization using natural superabsorbents like sodium alginate, incorporate natural antimicrobials for odor control, conduct rigorous clinical trials for safety validation, and develop tailored, low-cost machinery for decentralized manufacturing, ultimately ensuring this innovation achieves widespread adoption and impact.

REFERENCES:

1. Gokarneshan, N., Prabagar, M. M., Sathya, V., & Rachel, D. A. (2025). Design of a sustainable sanitary napkin using banana fibre. *Journal of Critical Research & Emerging Medicine, 4*(3), 1–6.

2. Tudu, P. N. (2024). Development of ecological absorbent core sanitary pads. *Scientific Research Publishing, 12*(2), 45–58.
3. Sharma, P., & Banerjee, R. (2025). Sanitary pads: Composition, regulation, and research challenges. *Journal of Materials Science, 60*(14), 10521–10536.
4. Zhang, Y., Chen, L., & Li, X. (2024). Comparative life-cycle assessment of hemp-based and conventional sanitary pads. *Journal of Cleaner Production, 420*(6), 138–149.
5. Kumar, V., & Singh, R. (2024). Revolutionizing sustainable nonwoven fabrics: The potential use of agro-waste fibers. *Energies, 4*(2), 115–128.
6. Adeola, A., & Joseph, O. (2024). Harnessing agricultural waste: From disposal dilemma to wealth creation. *Advances in Science & Technology Research Journal, 18*(3), 55–66.
7. Rani, S., & Thomas, M. (2024). Eco-conscious menstruation: An imperative need towards sustainable sanitary pads. *International Journal of Green Technology, 7*(1), 32–44.
8. Patel, A., & Gupta, S. (2023). Banana-based cellulose materials for advanced applications in hygiene products. *Carbohydrate Polymers, 315*(9), 120–131.
9. Bhatia, P., & Kaur, G. (2023). Innovation in biodegradable sanitary napkins using banana fibre, bamboo, and PLA. *Journal of Recent Advances in Sustainable Biology, 5*(2), 77–85.
10. Choudhary, R., & Meena, P. (2021). The potential use of agricultural waste and natural fibres for eco-friendly nonwoven products. *Journal of Natural Fibers, 18*(11), 1455–1468.
11. Sharma, P., & Gupta, S. (2021). Development of biodegradable sanitary napkins using banana pseudo-stem fibers. *Journal of Natural Fibers*, 18(4), 556–567.
12. Li, X., & Chen, H. (2021). Hydroentangled bamboo nonwovens for hygiene applications: Absorption and biodegradability. *Carbohydrate Polymers*, 261, 117879.
13. Das, R., Banerjee, S., & Saha, T. (2022). Jute–cotton blended absorbent cores for eco-friendly sanitary pads. *Sustainable Materials and Technologies*, 31, e00305.
14. Patel, A., & Mehra, V. (2022). Sugarcane bagasse cellulose as sustainable absorbent material for hygiene products. *Industrial Crops & Products*, 180, 114743.
15. Kumar, R., & Raj, P. (2023). Rice husk-derived nanocellulose for absorbent hygiene applications. *Cellulose*, 30(2), 989–1003.
16. Banerjee, K., Prasad, D., & Singh, N. (2023). Kenaf fiber reinforced PLA nonwovens for feminine hygiene products. *Journal of Cleaner Production*, 401, 136822.
17. Rani, M., & Thomas, J. (2023). Agro-waste fiber composites for sanitary absorbents. *Materials Today: Proceedings*, 72, 2225–2234.
18. Huang, Y., Lin, J., & Wang, L. (2023). Spunlace bamboo pulp nonwovens for sustainable sanitary napkins. *International Journal of Biological Macromolecules*, 235, 124101.
19. Singh, A., & Yadav, M. (2024). Hybrid agro-waste fibers in biodegradable sanitary pads: Performance evaluation. *Sustainable Materials and Design*, 15, 100245.
20. Mehta, K., & Yadav, S. (2024). Hydrogel composites from agro-fibers as eco-friendly superabsorbents. *Journal of Polymers and the Environment*, 32(3), 445–457.