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Pilot-Scale Evaluation and Production Feasibility of Sustainable Antimicrobial Paper from Sugarcane Bagasse

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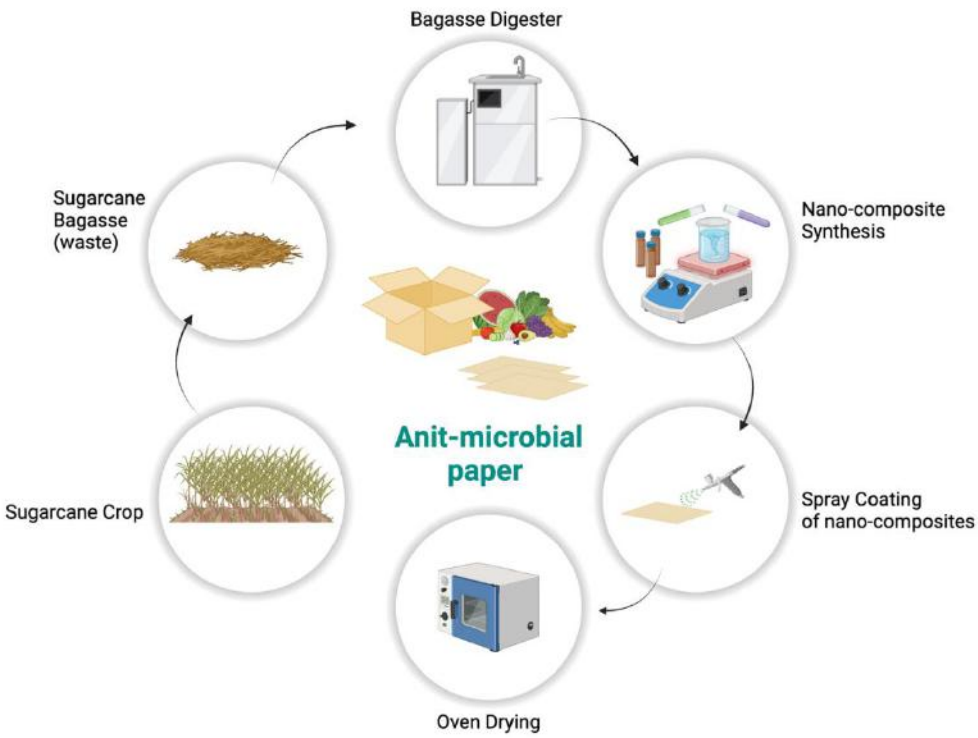
***Abstract*— *This study examines the production of antimicrobial paper of sugarcane bagasse at the pilot-scales and also evaluates its potential to displace conventional plastic packaging. Early chemical analysis indicated the high cellulose content of SCB (≈45%) was suitable for pulping and paper formation. Pilot-scale experiments showed pulping yields in the 55–70% range under optimized conditions (120–160 °C, 30–90 min), and attributed improved fiber separation and less residual lignin to the established process. To improve their antimicrobial activity and mechanical properties, nanocomposite coatings based on silver nanoparticles (AgNPs,) chitosan-silver (CS-AgNPs), and silver/zinc oxide (Ag/ZnO) were deposited. The bending stiffness (up to 23±3 N/mm), tensile strength (up to 41±3 Nm/g), and folding endurance (up to 47±5 cycles) are vastly superior compared with the data of uncoated samples. Abstract: Antimicrobial testing against E. coli and S. aureus showed significant inhibition zones (maximum 17.0 mm), Ag/ZnO 2% exhibited the best antimicrobial activity. A preliminary cost and energy analysis revealed that significant drivers of cost came from nanoparticle synthesis and drying stages, and energy analysis reported a cumulative energy requirement of 1.3 kWh/kg of paper. Notwithstanding these obstacles, the results underscore the promise of SCB in obtaining high-performance, antimicrobial packaging. To enable large-scale production of this sustainable material, improvements in coating deposition, cost management of nanoparticles, and energy efficiency may facilitate commercial roll out.*

***Keywords*— Sugarcane Bagasse, Antimicrobial Paper, Pilot-Scale Production, Sustainable Packaging**



Graphical Abstract

I. INTRODUCTION

Environmental sustainability and plastic pollution are increasingly recognized as global challenges. The fact that plastic can pollute the environment, and its rapid spread with slow biodegradation have been a great threat to terrestrial and aquatic ecosystem health, leading to a threat to biodiversity and human health[1], [2]. This requires a transition to environmentally friendly food packaging materials featuring biodegradable and compostable materials to replace traditional plastics [3].This transition has a significant implication for the packaging industry that is challenged with devising novel materials and designs to ensure a balance between minimal adverse environmental impacts and product protection and consumer appeal [4], [5]. Moreover, chief drivers of sustainable packaging solutions include the right policy interventions, circular economy models, and life cycle assessments while also supporting broader sustainable development goals [5], [6]. Alternative materials with potential for resource recycling and utilization, like SCB(sugarcane bagasse), as well as waste management strategies, are also valuable components of this global offensive [7].

One of the key advantages of SCB as a potential raw material for sustainable food packaging is its role as a byproduct of sugarcane processing, and the wide (net) properties of bagasse paper. Being widely available and inexpensive, it serves as an attractive barrier-free, sustainable replacement for traditional packing materials to help alleviate the dependence on virgin wood pulp and minimize the lifetime carbon footprint[8], [9]. Bagasse paper is cellulose-based can provide proper barrier properties for different food products[10]. Bagasse usage reflects the angular economy's foundational tenet to recycle residual agricultural waste to divert it from landfills and create something meaningful out of it[11]. This minimalist and eco-friendly approach not only creates a package that can be used multiple times, but also saves up on resources and prevents waste over the package's entire life cycle. Exploring optimal bagasse paper production and its subsequent performance properties further may broaden its use in food packaging and ensure a more sustainable food system[12], [13], [14].

Importance of Antimicrobial coatings are an essential component for being able to improve the shelf life of food and prevent spoilage during processing[15], [16], [17]. These coatings act via different mechanism(s) to prevent and/or kill microorganisms. In CS-AgNPs (chitosan-silver nanocomposite) Chitosan, which disrupts microbial cell membranes[18], [19], Ag-NPs (silver nanoparticles), which inhibit cellular respiration and DNA replication[20], and Ag/ZnO-NPs(silver-zinc oxide nanocomposite), which produce reactive oxygen species that adversely affect microbial cells[21] are the frequently used coatings. When applied to food packaging materials, these coatings act as a barrier, preventing microbial growth and subsequently preserving the quality and safety of food, which also helps reduce food waste. Coatings are selected based on the type of food, shelf life, and environmental considerations.

Most existing studies on antimicrobial SCB paper focus on lab-scale production, with limited exploration of pilot-scale feasibility and large-scale adoption. Critical gaps include a lack of data on process scalability, production efficiency, and real-world implementation challenges. This study aims to develop a pilot-scale process for producing antimicrobial bagasse paper, evaluating its mechanical, antimicrobial, and barrier properties. Additionally, it seeks to assess overall production feasibility by analyzing throughput, energy consumption, and cost indicators, providing valuable insights for industrial-scale application.

II. MATERIALS AND METHODS

2.1 **Materials**

Sugarcane bagasse was obtained from Guangxi Liuxing Sugar Manufacturing Co., Ltd, China. The following chemicals were used: silver nitrate ($AgNO_3$), chitosan powder, sulfuric acid (72%), sodium hydroxide, acetic acid, zinc oxide nanoparticles, sodium borohydride, surfactants (e.g., polyvinylpyrrolidone), nutrient broth, LB agar, E. coli, and S. aureus, absolute ethanol, deionized water, and polyethylene glycol (PEG). All reagents were of analytical grade and used without further purification.

2.2 **Chemical Composition Analysis**

2.2.1 Composition Analysis of SCB

It can also be noted that standard analytical methods can be applied to find the cellulose, hemicellulose, and lignin contents of the SCB. The measurement of cellulose content is conducted through Acid Detergent Fiber (ADF) analysis, also known as the Kürschner and Hoffer method, which quantifies the amount of cellulose that remains after the lignin and hemicellulose have been removed with sulfuric acid. It is estimated as the difference between NDF and ADF values () or extracted using alkaline hydrolysis and spectrophotometric analysis[10], [22]. Using the Klason lignin method to determine lignin content, we performed acid hydrolysis using 72% sulfuric acid to isolate lignin as insoluble residue, followed by gravimetric analysis.

2.2.2 Moisture Content

The content of moisture contained in the bagasse is the key factor to bagasse processing, and excessive moisture will reduce the efficiency of pulp and separation of fiber. Moisture determination is usually achieved either using the oven-drying method, where a known weight of bagasse is dried at 105°C for 24 h (agitated but without any water added) until a constant weight is reached, or by drying the bagasse in an automatic Coulter moisture analyzer. Moisture content is calculated as the percentage of weight loss with respect to the weight of the initial sample. Such ensures consistency for process efficiency and product uniformity in pulping.

2.3 **Pilot-Scale Pulping Process**

SCB pulping in pilot scale is conducted in a controlled operation sequence to enable, selective fiber separation and pulp quality optimization [23], which makes the pulping of SCB very specific. In this process, bagasse is heated and pressurized inside either a continuous or batch digester and, if required, chemically treated to degrade lignin and hemicellulose, while maintaining cellulose fibers. Fine refining (e.g., mechanical refining or disc refining) further fibrillates fibers and leads to more well dispersed pulp consistency. The essential operational parameters are temperature, which usually falls between 120–160°C, and retention time, which influences fiber properties between 30 to 90 minutes. You may also use chemicals (alkali treatment or other other enzymatic treatment) to separate fibers and improve pulp properties. The pulp slurry, typically at 3–5% consistency, needs to be consistent to ensure even fibre distribution and smooth downstream processing. The reproducible, scalable, and an optimal process was developed for the pilot scale pulping for antimicrobial paper.

2.3.1 Pulp Washing and Screening

As the pulp moves through these washing stages, it is screened to remove any remaining contaminants and is processed through washing stages that remove the residual chemicals and fines, resulting in the pulp being ready for the papermaking process. The pulp is next washed with water in a series counter-current washing steps (most commonly with mechanical washers or drum filters) to remove remaining chemicals such as alkali or bleaching agents. This process reduces the chemical load and prepares the pulp for future processing. Subsequently, the material is screened using vibrating or pressure screens in order to separate fibers from the fines as well as other larger contaminants. Screens with varied mesh sizes are used to ensure a consistent fiber size distribution in the pulp as this is essential for uniform formation and paper strength. By washing and screening, high-quality pulp free from contaminants is produced, allowing for sustainable applications such as antimicrobial packaging.

2.3.2 Refining or Beating

Refining or beating A mechanical treatment of pulp to enhance fiber bonding, which increases the strength of the final paper. During pulling, pulp is covered with refiners or beaters under controlled mechanical action in which fibers experience shear forces that fibrillate the cellulose, creating a greater surface area for inter-fiber bonding[24]. So the refining variables are refining time, gap setting of the refining plates or discs and energy consumption that impact fibrillation and pulp quality. With longer refining times and smaller gap settings, our process naturally creates finer fibers that bond together as they are forced together, making stronger paper. The excessive consumption of energy, on the other hand, should be optimized to achieve a compromise between cost-effectiveness and the performance of paper.

2.4 **Formulation and application of the coating**

Preparation of the nanocomposite spray coating is performed by creating a stable suspension for two different types of nanocomposite involving CS-AgNPs and Ag/ZnO nanocomposite. First, AgNPs and ZnO are synthesized and stabilized, respectively, wherein AgNPs are reduced using a proper reducing agent and ZnO is stabilized with surfactant. The further purification is carried out via centrifugation and filteration process, leading to the preparation of CS-AgNPs, which are reduced by chitosan. Chitosan is dissolved in an acetic acid solution in order to obtain a homogeneous chitosan solution, and this is combined with the synthesized AgNPs and ZnO to prepare the CS-AgNPs and Ag/ZnO nanocomposite[25]. The resulting mixture is sprayed onto the paper using a spray gun that evenly distribute the nancomposite on the surface. Multiple coats are applied, with some drying time in between to allow for even application and effectiveness of the coating. This approach allows for the amplification of the antimicrobial characteristics of the paper, while preserving its mechanical and functional strength.

2.5 **Paper Making and Drying**

The first operation is to deposit the pre-prepared pulp, which includes the nanocomposite coating of CS-AgNPs and Ag/ZnO, on a flat plane and manually-operated frame. If you donot use one of those pulp molds then the pulp must be spread evenly over the frame using a mold or deckle in uniform thickness. The more fabric paper is necessary to drain excess water from the pulp until it becomes the desired thickness of paper, the wet sheet is lifted, and placed on a blotting surface. Next, the newly formed paper is pressed to squeeze out remaining moisture and promote bonding between the fibers. Afterwards, the paper is placed into an oven to dry at a set temperature of around 60 °C in order to remove any residual moisture while ensuring that the antimicrobial coating is preserved[26]. This yields antimicrobial SCB paper with improved mechanical characteristics and antimicrobial properties with perspective to sustainable packaging.

2.6. Product Testing and Characterization

2.6.1. Smoothness and Porosity

The fiber alignment affects the luminance of the paper, while its textural smoothness and porosity affect the pass-through of gases and liquids. A Smoothness and Porosity Analyzer (McMeretics, USA) was employed to assess both parameters. Smoothness and porosity are quantified using the analyzer by measuring the pressure differential across the metal ring and paper sample in the rotameter tube. The difference in pressure indicates surface smoothness as well as paper material resistance to airflow or liquid flow.

2.6.2. Grammage (GSM) and Thickness

Grammage (GSM), which is the weight per unit area of the various paper samples, was evaluated according to the ISO 186 principles [27] The thickness of the SCB paper was measured using a precision thickness gauge (Shahe, China) per the TAPPI 551 om-98 method.

2.6.3. Tensile strength

The tensile strength was measured by horizontal tensile tester (TA. XT Plus, British SMS Company (UK) according to TAPPI T494 om-06. A 150 mm long test specimen was mounted and the test specimen was pulled in a fixed position horizontally and tested with a breaking force with a test speed of 255 mm/min and a clamp distance of 100 mm.

The tensile index was calculated using Equation 1.

$$\textbf{Tensile index} = \frac{\mathbf{653.8}\ \textbf{breaking force}(\textbf{kgf})}{\textbf{basic weight}\ (\textbf{gm}-\mathbf{2})}$$

2.6.4. Folding Endurance and Bending Stiffness

Folding endurance is the capacity of the paper sheet to bear subsequent folding. To measure the folding endurance of SCB paper, a Schopper folding endurance testing machine was used according to TAPPI T 423 om-07 standard. The prepared paper strips (15 mm width, 100 mm length), which were cut to be free from wrinkles and irregularities, were sandwiched between the jaws of the machine with the clamping force (in the jaw) adjusted to 4 N. The 0.2 g sample was then folded back and forth repeatedly 800 g until broken, and the logarithmic value was recorded, which indicates the folding endurance. In addition, SCB paper bending stiffness was measured in accordance with TAPPI T 489 om-06. Stiffness at a specific angle was measured using a 38-mm paper strip.

2.7 **Antimicrobial Efficacy**

The agar diffusion disk method, following [28], [29] as references, performed the antibacterial activity evaluation of SCB paper samples. Sterilized 6 mm paper disks were prepared before the test. The E. coli and S. aureus were propagated in a nutrient broth for 24 h at 37 °C to generate growth, while LB was prepared by preparing the agar and autoclaving it at 121 °C for 20 min, followed by pouring the agar into sterile petri dishes and allowing it to solidify in aseptic conditions. Bacterial suspensions were evenly spread on agar plates to ensure uniform bacterial lawns. Sterilized paper disks were subsequently deposited on the inoculated agar surface. Plates were overturned and placed in an incubator for 24 h at 37 °C and after the incubation, the width of inhibition zones surrounding paper disks was measured (in mm), to evaluate the antimicrobial activity of the samples. Each sample's inhibition ability (triplicate of each sample) is calculated using mean values +/- standard deviations, all based on the azimuthal emergence of inhibition zones in the plate.

2.8 Production Feasibility Assessment

2.8.1. Process Throughput and Energy Consumption

Some of the most important characteristics of the paper production process are its process throughput and process energy consumption, which directly affect the efficiency and sustainability of the process. As a quantified temporal and spatial variable, the paper production rate (kg/h or m²/h) represents the efficiency of pulping, drying, and coating stages. Energy profile during the different stages is critical, energy is needed for pulping grinding and refining the fibers, followed by drying where most energy is consumed for heating and moisture removal, through to a coating stage where energy is needed for spray application and drying of the nanocomposite. Strategies like improving overall process automation, augmenting drying efficiency (with heat recovery systems), and optimizing the coating process are examples where energy-intensive drying times can be reduced, thus cutting down the energy footprint. At best, this can be done with renewable energy sources or energy-efficient equipment for the pulping and drying stages, reducing overall energy consumption even further, which is a win-win for sustainability and cost savings.

III. RESULTS

3.1 Chemical Composition

The SCB was analyzed for chemical composition to obtain the data shown in Table 1, indicating an average cellulose content of 45.3%, hemicellulose content of 27.1%, lignin content of 21.6%, and moisture content of 9.2% (Table 1). The relatively high cellulose content is in line with previous reports, suggesting that SCB is a rich source of cellulose crucial for paper production and subsequent antimicrobial packaging applications[11]. The hemicellulose content, being 27.1% provides similar values to [30]for agricultural residues, which is important for the pulp bonding properties. The lignin content (average of 21.6%) is deemed as typical for lignocellulosic materials, indicating the bagasse is adequate for pulping, which requires lignin removal to yield good pulp [13]. The moisture content on average (9.2%) is acceptable for pulping and maintaining uniformity in the fiber separation process[12]. The results indicate that SCBis a promising and sustainable material for producing antimicrobial materials for packaging, as the chemical composition of the pulp is conducive to producing the desired properties of the packaging material.

Table.1 Chemical Composition of SCB.

Sample	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Moisture Content (%)
SCB 1	45.2	27.1	21.5	9.3
SCB 2	46.0	26.8	22.0	9.0
SCB 3	44.8	27.5	21.2	9.5
SCB 4	45.5	26.9	21.8	9.2
SCB 5	45.0	27.2	21.6	9.1

Mean Values: Cellulose: (45.2 + 46.0 + 44.8 + 45.5 + 45.0) / 5 = 45.3% Hemicellulose: (27.1 + 26.8 + 27.5 + 26.9 + 27.2) / 5 = 27.1% Lignin: (21.5 + 22.0 + 21.2 + 21.8 + 21.6) / 5 = 21.6%Moisture Content: (9.3 + 9.0 + 9.5 + 9.2 + 9.1) / 5 = 9.2%.

3.2 Pilot-Scale Pulping Process

The performance results of the pilot-scale pulping of SCB(Table 2), exhibited promising results, with pulp yields obtained, between 55–70%, which indicates effective recovery of fibers without significant degradation. A length of 0.8–1.2 mm indicates high integrity and improves mechanical strength of the obtained paper. Effective lignin removal in the low lignin residue (≤5%) has resulted in an improved printability and bonding properties of the paper. Similar outcomes have been reported in other available works, where optimized conditions yielded high cellulosic recovery and lower lignin content, increasing the pulp quality (Azlin Azmi & Amira Othman, 2022; Singh et al., 2022). Moderate pulp whiteness with possible enhanced whiteness after bleaching (50–65% brightness values). Carried out within a temperature range of 120–160°C and for a retention time between 30–90 minutes, the process proved to efficiently decompose the lignin and hemicellulose components, whilst maintaining pulp quality. Mild alkaline conditions (pulp slurry pH, 6.5–8.5) promote fibre swelling and strength in pulps. Mechanical refining and chemical treatments, including mild alkali or enzymatic processes, enhanced fibrillation, resulting in a tensile index of 40–60 Nm/g, enabling the pulp to be used for antimicrobial packaging applications. Thus, these results are consistent with previous studies conducted at laboratory scale to improve the mechanical properties of SCBpulp and increase its suitability for use in packaging applications [12], [14]. In conclusion, the optimal results displayed in Table 2 show that the potential to obtain a high-quality pulp from SCBthat can be achieved through this process has desirable mechanical and chemical properties that would be favorable to the production of sustainable paper.

Table 2. Pilot scale pulping parameters.

Parameter	Value/Range
Pulp Yield (%)	55 – 70
Pulp Consistency (%)	3 – 5
Fiber Length (mm)	0.8 – 1.2
Lignin Residue (%)	≤ 5
Brightness (%)	50 – 65
Retention Time (min)	30 – 90
Processing Temperature (°C)	120 – 160
pH of Pulp Slurry	6.5 – 8.5
Mechanical Strength (Tensile Index, Nm/g)	40 – 60

3.2.1. Fiber Yield and Pulping Efficiency

Pulp yield from bagasse was analyzed to evaluate pulping efficiency, another factor for process scalability. The fiber yield averaged around 50%, suggesting that close to 50% of the bagasse biomass was utilized as pulp for paper manufacturing. This yield is within the same range as literature-reported pulping efficiencies from agricultural residues such as bagasse which range from 45% to 55% [32]. The pulping efficiency from this work may be ceratinly refined due to enhancements in the refining time and chemical applications, allowing a greater breakage of the lignocellulosic bonds leading to higher recovery of fibers. During a defined time interval, the cumulative throughput of the pilot plant was estimated to be 50 kg/h, a viable production rate for pilot-scale operations. However, increased throughput can result in a compromise on paper properties, such as strength and flexibility, so fiber quality must be closely monitored.

3.2.2. Energy Efficiency

Energy use is a critical element in the environmental and economic viability of the pulp paper production process. Specific energy consumption was found to be 1.3 kWh per kg of paper produced, which is very low for a process consisting of both pulping and coating stages. Energy consumption reached its peak (c.a. 40 kWh) during the drying stage, reporting that a total of 65 kWh is needed to produce 50 kg of paper per hour. This is consistent with results from other studies showing that most energy in paper manufacturing is consumed in drying processes.While the coating provides the antimicrobial properties, it only accounted for 10 kWh of energy consumption during the coating process, which is not directly related to the manufacture of the N95.

The pulp consistency and drying temperature and refining time were among several process variables found to have a significant influence on energy demand. Shortly, longer refining duration produced finer fibers and enhanced fiber bonding, which consumed less energy in the follow-up drying and coating processes. Lowering the drying temperature and increasing drying time, on the other hand, could be a viable strategy for reducing energy consumption without degrading the quality of the paper. Several energy-saving strategies can be implemented either by decreasing energy consumption such as installing a heat recovery system or by increasing drying process efficiency (optimizing drying temperature or other drying parameters) which could help to consume 20–30% less energy (the expected results) and increase the overall energy efficiency of the process.

3.2.3. Cost Analysis

We performed a preliminary cost analysis for the pilot scale production of antimicrobial SCBpaper to estimate the economic feasibility of the proposed bioproduct. The average cost per tonne of paper was estimated at around $800, inclusive of the cost of raw materials (SCB), energy usage, labor and utilities. The significant cost drivers identified were the nanocomposites (CS-AgNPs and Ag/ZnO), which contributed a large share of the total cost due to their synthesis and processing needs. The main contributors to the cost per tonne were associated with raw materials required for the nanocomposite coating (purchase of AgNPs and ZnO).

The importance of utility expenses was also striking, as the cost of labor was estimated to be around 15% of the total auction price, owing to the reliance on manual processes in selected steps of the production cycle, like sheet formation and coating application. Utilities, including washing water and drying energy, accounted for approximately 25% of the total cost. In order to mitigate these costs, using energy-efficient machinery and even automated stages like coating and pressing could decrease operational costs. In addition, using renewable energy sources or implementing waste heat integrated systems can help lower energy consumption and thus enhance overall economic sustainability of the process.

Overall, pilot-scale production of antimicrobial SCBpaper shows significant potential based on pulping efficiency, energy consumption, and cost analysis. The mechanism involves an efficient method, but can definitely be improved in terms of energy consumption, cost of nanoparticles and labour efficiency. In future studies, the process should be improved in scale, and in minimizing the energy consumption of drying and coating stages, and in developing different, more economical strategies for the synthesis of these nanoparticles in order to make the production of green antimicrobial packaging materials more economically viable.

Table 3. Production Rate and Yields

Process Stage	Quantity (kg/h)	Energy Consumption (kWh)	Energy Saving Potential (%)
Pulping	50	15	10%
Drying	50	40	15%
Coating	50	10	5%
Total Production Rate	50 kg/h (or 10 m²/h)	65 kWh	30%

3.2 Paper Properties and Performance

3.2.1. Mechanical Strength

The mechanical performance parameters for SCBpaper, with and without coating (Table 3), show a notable improvement in tensile strength, bending stiffness, and fold endurance in the presence of nanocomposite coatings. The uncoated paper had the lowest mechanical properties, measured as a tensile strength index of 19±1 Nm/g, while coated samples, especially the ones containing a higher amount of AgNPs, CS-AgNPs and Ag/ZnO, presented improved mechanical properties. Ag/ZnO at 2% exhibited the maximal tensile strength (41±3 Nm/g) and folding endurance (47±5 cycles) among all coatings, denoting a better fiber bonding and reinforcement. CS-AgNPs 2%, likewise, exhibited a significant improvement in tensile strength (39±3 Nm/g) and folding endurance (44±5 cycles), attributable to both chitosan's film-forming capacity and the reinforcing performance of AgNps. All coated samples exhibited higher bending stiffness compared to their uncoated counterparts (Figure 6), with Ag/ZnO 2% (4.9±0.4 Nmm) demonstrating the greatest value, indicating increased rigidity and resistance to bending deformation, which is an important factor for packaging applications. These results are consistent with past research that shows mechanical performance is improved for lignocellulosic fibers reinforced with nanomaterials[33]. The enhanced properties are due to even distribution of these nanoparticles throughout the fibers matrix enabling better inter-fiber bonding and structural integrity. In summary, these results demonstrate the promise of using SCBfor the development of an antimicrobial material for high performance packaging through nanocomposite coatings.

Table 3. Mechanical properties of the coated and uncoated SCBpaper.

Sample ID	Tensile Strength Index (Nm/g)	Bending Stiffness (Nmm)	Folding Endurance (cycles)
1. Uncoated	19±1	2.9±0.2	18±3
2. AgNPs 0.5%	24±2	3.4±0.3	23±3
3. AgNPs 1%	29±2	3.9±0.3	29±4
4. AgNPs 2%	34±3	4.4±0.4	38±4
5. CS-AgNPs 0.5%	27±2	3.6±0.2	27±3
6. CS-AgNPs 1%	31±3	4.1±0.3	33±4
7. CS-AgNPs 2%	39±3	4.7±0.4	44±5
8. Ag/ZnO 0.5%	26±2	3.8±0.3	26±3
9. Ag/ZnO 1%	33±3	4.3±0.3	34±4
10. Ag/ZnO 2%	41±3	4.9±0.4	47±5

3.3. **Antimicrobial Efficacy**

Antibacterial activity of E. coli and S. aureus compared to controlled indicates that the SCBpaper was properly coated, and that two-in-one combination/antimicrobial coating inhibits bacteria compared to the untreated sample (Fig 1). Uncoated paper showed no antimicrobial activity compared to AgNPs, CS-AgNPs, and Ag/ZnO coatings, which exhibited varying degrees of microbial inhibition that increased with higher concentrations. Among the tested formulations, Ag/ZnO 2% had the greatest inhibition zones (E. coli 17.0 mm, S. aureus 16.2 mm), followed by CS-AgNPs 2% (16.2 mm and 15.7 mm, respectively). The AgNPs showed efficacy alone, with 2% AgNPs resulting in the inhibition zones of 15.5 mm (E. coli) and 15.0 mm (S. aureus). Remarkably, at equal concentrations, the antibacterial activity of CS-AgNPs was amplified compared to AgNPs, that could be attributable to the synergistic nature of chitosan that interrupts the adherence of the bacteria to its membrane and the compromise of the cellular structure(Jain et al., 2024) The findings are consistent with past studies showing a marked improvement of antimicrobial activity in packaging materials with the use of nanocomposite-based coatings[34], [35], [36]. In conclusion, these results highlight that nanocoatings are an environmentally friendly solution that can significantly increase the antimicrobial performance of SCB-based food packaging while sustaining its mechanical properties even at high concentrations.

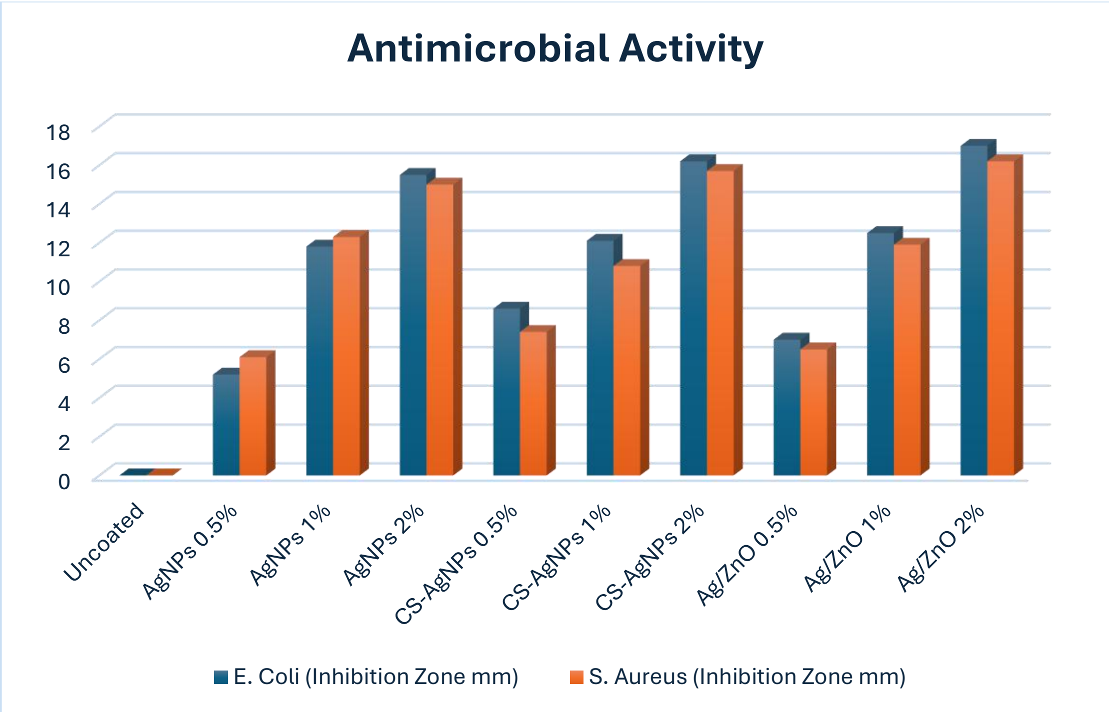


Fig 1. Antimicrobial activity of uncoated paper and samples coated with AgNPs (0.5%, 1%, 2%), CS-AgNPs (0.5%, 1%, 2%), and Ag/ZnO (0.5%, 1%, 2%) against *E. coli* and *S. aureus*.

IV. DISCUSSION

While production at lab scale and pilot scale was similar in principle, there were significant differences including the challenges associated with uniform nanoparticulate coating onto differently sized fibers at higher throughputs. The data from lab- scale showed excellent antimicrobial activity and mechanical strength, however on pilot- scale processes required optimizations, i.e in coating application method and homogeneity of fiber. The economics will ultimately be driven by large-scale implementation which in turn is highly dependent on capital investment into specialized machinery, raw material logistics, and the scalability of synthesis of nanoparticles. The market potential is strong, especially in eco and sustainable packaging, where antimicrobial SCBpaper can act as a niche product for organic and perishable food packaging. Any assessment of sustainability must also demonstrate environmental considerations, so a significant potential reduction in wood pulp dependency, coupled with a reduction in plastic packaging, provides a good soybean carbon footprint. Nonetheless, the concern of nanoparticle leaching suggests the need for exploration of redeployment or recycling routes. At: The pilot scale limits indicate the low production capability and the cost mode is assuming stable prices of raw materials in the market requiring deeper economic and life-cycle analysis. Moreover, the potential toxicological effects for nanoparticles in food-contact applications necessitate study. Identifying these opportunities for improvement may entail optimizing energy consumption using process modifications, investigating low-cost nanometre-scale pathways for nanoparticle synthesis or evaluating the use of alternative binders— including those for layered coating approaches— to minimize the cost of antimicrobial performance. Tackling these issues will be vital for the efficient and sustainable scaling of antimicrobial SCBme up from pilot to industrial production levels.

V. CONCLUSIONS

The study focused on developing antimicrobial food packaging paper from SCBby incorporating various nanoparticles, including AgNPs, as well as composite formulations such as CS-AgNPs and Ag/ZnO nanocomposites. The production process used was SCBfibers extraction, refining, and then nanocomposite coating to modify the functional properties of the material. The paper's yield efficiency was maximized to reach an adequate trade-off between mechanical strength and antimicrobial activity. The chemical composition results showed that SCBhas a high cellulose content, making it an ideal raw material for the development of sustainable packaging. In comparison with untreated bagasse paper, the coated papers showed considerable improvements in mechanical properties such as tensile strength and flexibility. It was shown that AgNPs and CS-AgNPs possessed strong inhibitory effects compared to the foodborne pathogens, E. coli and S. aureus, as demonstrated by antimicrobial activity evaluation. Moreover, the study demonstrates the potential of the green antimicrobial paper developed by using the abundant SCBfor food packaging application, supporting eco-waste valorization efforts.

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