

Eco-Friendly Bamboo Degumming Using Sequential Steam Explosion, Alkali, and Anaerobic Digestion

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Abstract: This study has advanced a new sequential degumming technology of bamboo using steam explosion, alkali treatment and anaerobic digestion. Steam explosion at 7 kg/cm² for 8 min achieved 22.2% degumming, while 10% NaOH boiling for 2 h further increased degumming to 45.7%. Subsequent anaerobic digestion for 3 days using a microbial consortium reduced lignin to 10.58%, hemicellulose to 13.54%, and pectin to 0.7%, yielding fibers with 75.2% cellulose content. SEM analysis confirmed progressive fiber individualization with attached microbes on partially degummed surfaces and clean, smooth fibers after complete treatment. The ultimate lignin percentage (10.58) can be compared to chemically degummed bamboo but under less aggressive conditions (38 o C) with less chemical added. This is a sequential chemobiological method that provides a better alternative to the production of bamboo fibers, which is more sustainable.

Keywords: Bamboo Degumming; Steam Explosion; Anaerobic Digestion; Natural Fibers; Sustainable Textiles.

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I. INTRODUCTION

The textile industry is under the pressing needs to transition to the use of the sustainable sources of materials as the environmental effects of the traditional fiber production are drastic. Water and pesticides are required in large quantities to produce cotton, and man-made fibers that are based on petroleum are the source of a continuous supply of microplastic pollution. This unsustainable paradigm necessitates the creation of high-performance, renewable alternatives. Bamboo has become a very promising raw material for the production of sustainable textiles. Among the fastest-growing plants, this perennial grass has exceptional renewability, allowing for ongoing biomass production and carbon sequestration by regenerating from large rhizome systems without the need for replanting [1]. Compared to cotton, bamboo farming uses fewer agrochemical inputs and usually depends on natural precipitation [2]. Moreover, it has a broad root system, which improves the soil structure and increases the ease of restoration of degraded sites [3].

Nevertheless, there is an underlying contradiction to the use of bamboo: raw bamboo is astonishingly tough lignocellulosic composite where cellulose microfibrils are impregnated within and bonded by an amorphous system of lignin, hemicellulose and pectin collectively known as gums although the final product of bamboo is a soft handle fabric [4]. Since cellulose fibrils are bound together by the lignin hemicellulose matrix, separating individual filaments requires removing the middle lamella and main wall [5]. This crucial procedure, known as degumming, requires removing amorphous colloidal materials without sacrificing the strength of the fiber. The most recent technique, chemical degumming, uses alkalis to hydrolyze gum components [6] but it requires significant chemical inputs at high temperatures, producing effluent with a high chemical oxygen demand [7] and possibly breaking down cellulose fibers [8]. An efficient physico-chemical pretreatment for lignocellulosic biomass is steam explosion, which involves exposing raw materials to saturated steam at high pressure and then abruptly decompressing them. By physically rupturing the stiff fiber structure and causing auto-hydrolysis of hemicellulose, this quick steam expansion increases the surface area that is accessible. The dense

composite structure of bamboo is efficiently disrupted by steam explosion, which partially dissolves hemicellulose and redistributes lignin, improving processability [9].

Anaerobic digestion is an entirely novel and unexplored biological method of degumming. To break down complex lignocellulosic matrices, anaerobic microbial consortia create a synergistic array of enzymes, such as cellulases, hemicellulases, and different lignin-modifying enzymes [10, 11]. Potential benefits of using mixed microbial cultures in controlled anaerobic environments include the ability of the microbial community to adapt to the substrate, which may result in more thorough and effective breakdown of non-cellulosic components while maintaining the integrity of cellulose. However, because bamboo's resistant natural structure might restrict microbial colonization and enzyme penetration, the effectiveness of such anaerobic systems heavily depends on the substrate's accessibility [12]. Thus, the hypothesis of this study was that native bamboo structure would be efficiently disrupted by a combination of steam explosion and alkali boiling pretreatment, making it particularly vulnerable to future bio-degumming by anaerobic digestion.

II. MATERIALS AND METHODS

➤ Chemicals and Equipment

Culms of fresh Moso Bamboo, around two years old, were gathered from China's Jiangxi province. A hand wood peeler was used to make thin bamboo strips which were used for all experiments. For steam explosion experiments, traditional Chinese popcorn machine was used. Chemicals including sodium hydroxide (NaOH, AR, ≥96%, reagent, Shanghai Titan Scientific Co., Ltd., China), was of analytical

grade. The pilot-scale Spiral Symmetry Stream Anaerobic Bioreactor (SSSAB) at the site of a wastewater treatment project for soybean products supplied the anaerobic granular sludge (AGS) for inoculating the bioreactor.

➤ Steam Explosion and Alkali Pretreatment

Bamboo strips were soaked in water at 50°C for 1hour. Load the soaked bamboo into explosion device and heat up. When pressure rises to a certain value, it is maintained for a period of time, opened the vent valve and collected the bamboo fibers sprayed out due to explosion. The bamboo after steam explosion was then boiled in pressure cooker for 1 hour with different concentrations of NaOH to further soften the recalcitrant structure of bamboo chips.

➤ Anaerobic Degumming

After the pretreatment, bamboo strips were then put into serum bottles along with anaerobic microbes. Oxygen was removed from the serum bottles by blowing nitrogen and sealed tightly. These bottles were kept in shaker water bath at 38°C for 3 days. Degummed bamboo fibers were removed from the anaerobic sludge and tested the chemical composition and morphology.

III. RESULTS AND DISCUSSION

➤ Effect of Steam Explosion Pressure and Holding Time

The degumming rates at various steam explosion pressures and holding times are displayed in Figure 1. Despite a shorter holding time (8 min), degumming increased slightly from 7.8% at 5 kg/cm² to 8.4% at 6 kg/cm² before rising abruptly to 22.2% at 7 kg/cm². This suggests a key pressure threshold for successful structural disruption.

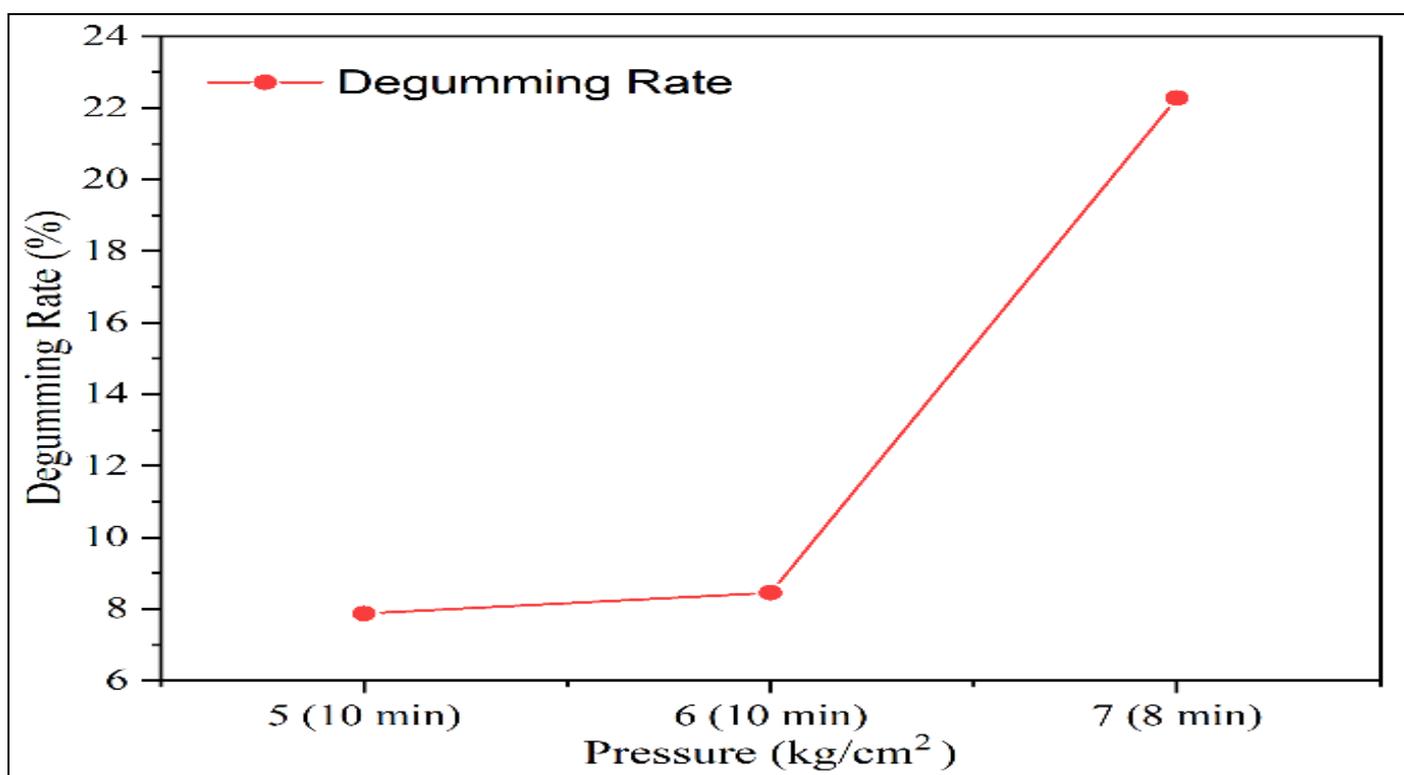


Fig 1 Effect of Steam Explosion Pressure on Bamboo Degumming Rate

Steam explosion pressure had a major impact on the degree of fiber separation and color change. The bamboo was light yellow and mostly intact after 10 minutes at 5 kg/cm², suggesting that the lignocellulosic structure was not severely disrupted. A brownish-yellow color and coarse fiber separation were the results of increasing the pressure to 6 kg/cm² (10 min), indicating a partial disintegration of the fiber bundles. The bamboo turned brown with well-dispersed individual fibers at the maximum pressure of 7 kg/cm² with a slightly shorter holding time of 8 minutes, indicating extensive defibration and structural disruption and proving to be the most effective condition for upsetting the bamboo structure before further processing.

➤ Effect of Alkali Concentration

All non-cellulosic components were gradually decreased by increasing the alkali concentration and treatment duration, as indicated in Table 2. After one hour of treatment with 5% NaOH, lignin decreased to 20.68%, hemicellulose to 22.23%, and pectin to 1.5%. Lignin further dropped to 18.37%, hemicellulose to 20.09%, and pectin to 1.3% at 7% NaOH for a longer period of time (1.5 hours). Lignin 16.14%, hemicellulose 17.00%, and pectin 1.0% were the lowest values obtained by the most severe treatment, 10% NaOH for two hours, which was chosen as the ideal alkali pretreatment condition for further research.

➤ Combined Pretreatment and Anaerobic Digestion

According to Table 3, fresh bamboo had 1.9% pectin, 25.61% hemicellulose, and 23.0% lignin. Lignin dropped to 15.6%, hemicellulose to 15.37%, and pectin to 0.9% following the combination treatments. After anaerobic digestion, more reductions took place, reducing pectin to 0.7%, hemicellulose to 13.54%, and lignin to 10.58%. Anaerobic digestion successfully targets leftover lignin following chemo-mechanical pretreatment, as evidenced by

the maximum hemicellulose removal during pretreatment and the significant lignin removal during digestion.

➤ Morphological Changes (SEM)

SEM images of bamboo fibers following thorough sequential degumming are shown in Figure 2. Microbial colonization and activity during the biological degumming stage are confirmed by Figure 2a, which shows a fiber surface with little remaining gum and associated anaerobic microorganisms. Effective fiber individualization and the successful removal of non-cellulosic components are demonstrated by Figure 2b, which displays a smooth, clean fiber surface free of visible debris. The anaerobic microorganisms effectively colonized the pretreatment bamboo and eliminated all remaining gums, producing high-quality degummed fibers, as these images collectively show.

➤ Comparison with Conventional Methods and Limitations

The final 10.58% lignin percentage attained in this investigation is similar to values documented for bamboo fibers that have been chemically degummed (usually 8-12% lignin) [13]. Crucially, this was accomplished with less chemical input and under mild biological circumstances (38°C), potentially providing environmental benefits over traditional chemical degumming, which necessitates high temperatures (90–100°C) and produces wastewater that is extremely polluting [7].

Nevertheless, it should be noted that there are several constraints. The microbial community that performed lignin removal was not characterized, and the 3-day anaerobic digestion period may be the period that is long to be used in the industrial setting. Moreover, each research was conducted on a laboratory level. To get over these limitations, future study should employ process optimization, microbiological characterization, fiber quality testing, and scale-up investigations.

Table 1 Specification of Bamboo after Steam Explosion

Steam explosion pressure (kg/cm ²)	Pressure holding time (min)	Colour of Bamboo	Appearance of Bamboo
5	10	Light yellow	Almost no fiber separation, bamboo still in strips form
6	10	Brownish Yellow	Coarse fiber separation
7	8	Brown	Dispersed fibers

Table 2 Chemical Composition after Alkali Pretreatment

Alkali Concentration	Lignin	Hemicellulose	Pectin
5% NaOH (1h)	20.68%	22.23%	1.5%
7% NaOH (1h & 30 min)	18.37%	20.09%	1.3%
10% NaOH (2h)	16.14%	17%	1%

Table 3 Chemical Composition of Bamboo Fibers at Three Key Stages of the Sequential Degumming Process

Methods	Lignin	Hemicellulose	Pectin
Fresh Bamboo	23%	25.61%	1.9%
Alkali & Steam explosion combined	15.6%	15.37%	0.9%
After Anaerobic digestion	10.58%	13.54%	0.7%

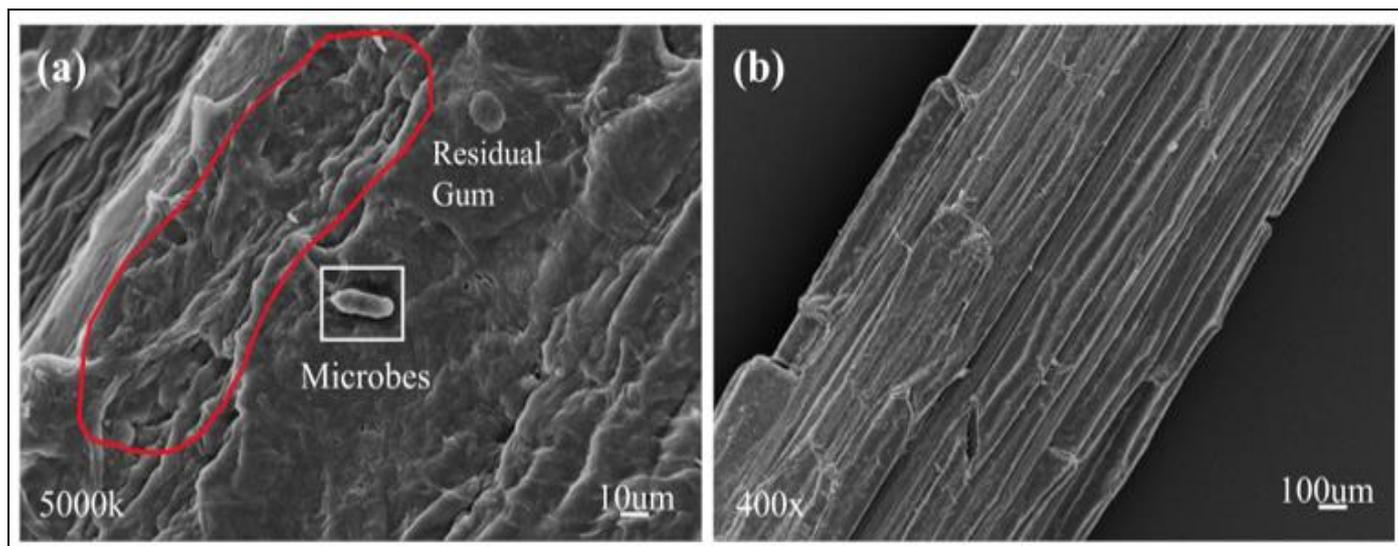


Fig 2 SEM Analysis of Surface Morphology of Degummed Bamboo (a) Attached Microbes and Residual Gum (b) Smooth Surface of Degummed Bamboo Fiber.

IV. CONCLUSION

This experiment was able to show a sequential process of degumming using steam explosion (7 kg/cm², 8 min), alkali boiling (10 percent NaOH, 2 h), and anaerobic digestion (3days, 38 C). The procedure lowered lignin and hemicellulose and pectin, producing fibers that are 75.2% cellulose. The synergistic advantages of chemo-mechanical pretreatment followed by biological treatment were confirmed by the selective targeting of residual lignin by anaerobic digestion. Effective fiber individualization and microbial colonization were demonstrated by SEM examination. It is a more sustainable variant of the traditional chemical process of degumming, but the time of digestion and the characterization of fibers should be optimized to apply it in the industry.

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