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Bamboo Fibre as a Sustainable Alternative to Conventional Surgical Cotton: A Review Formulation Considerations, Comparative Properties, Pharmacopoeial Evaluation, and Limitations

Revati A. Thengzode, Sakshi A. Gawali, Resha V. Dukare, Sakshi A. Pole, Sanjana M. Palaskar
Dr. R. H. Kale, Dr. S. L. Khedekar
PRMSS Anuradha College of Pharmacy, Chikhli, Buldhana, Maharashtra, India
Sant Gadge Baba Amravati University, Amravati

Abstract: *Absorbent (surgical) cotton, prepared from the seed hairs of Gossypium species, remains a core material in wound care and surgery. Concerns about the water, pesticide and land demands of cotton cultivation have encouraged the search for renewable cellulosic alternatives. Bamboo, a fast-growing perennial grass that regenerates from its own rhizome, is one candidate. This review outlines how surgical cotton is produced and classified, describes the botanical, chemical and physical features of bamboo fibre, compares bamboo and cotton fibre, and discusses extraction routes, possible wound-care applications, advantages, limitations, and the pharmacopoeial parameters against which a bamboo-based absorbent cotton should be evaluated. Evidence specific to bamboo as a pharmacopoeial-grade absorbent cotton is limited; most published work concerns bamboo fibre in textiles, composites and experimental wound dressings. Key gaps include standardisation, heavy-metal safety, and head-to-head testing against official monographs*

Keywords: Bamboo fibre; surgical cotton; absorbent cotton; sustainable biomaterials; wound dressings; pharmacopoeial evaluation.

I. INTRODUCTION

Surgical cotton, also called absorbent cotton wool, is one of the oldest and most widely used materials in healthcare. It serves for wound cleaning, dressing, padding, swabbing and as an absorbent barrier during surgery. Despite the many synthetic and semi-synthetic wound-care products now available, it remains in hospitals, clinics and household first-aid kits because of its softness, high absorbency, low cost and biocompatibility. It is purified, bleached and carded until it meets the purity and absorbency requirements of pharmacopoeias such as the Indian Pharmacopoeia (IP), British Pharmacopoeia (BP) and United States Pharmacopeia (USP) [11–13].

Growing attention to the environmental footprint of raw materials now extends to pharmaceuticals and healthcare disposables. Conventional cotton cultivation is associated with intensive irrigation, heavy pesticide and fertiliser use, soil degradation and a comparatively long crop cycle; assessments of the water footprint of cotton consumption identify it as a water-intensive crop whose impacts fall largely in the producing regions [6]. Cotton is a biodegradable cellulosic fibre, but the scale of consumption of disposable medical products, together with resource-intensive farming, has led researchers to look for natural fibres that can match cotton's performance with a smaller ecological footprint.

Bamboo is a fast-growing, high-yielding grass that reaches harvestable maturity in roughly three to five years, needs little irrigation and pesticide input, and regrows from its root system after harvest [10,14]. Bamboo fibre is rich in

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cellulose and has a porous, honeycomb-like microstructure that supports moisture absorption and wicking [2]. Bamboo has also been described as containing a natural antimicrobial substance popularly called 'bamboo kun', although this claim is debated and is generally weaker for chemically regenerated fibres [8,9]. These features make bamboo an attractive raw material for a biodegradable absorbent cotton, which is the motivation for this review.

A. Scope

The aim of this review is to collate what is known about bamboo fibre that is relevant to its possible use as a substitute for surgical cotton, and to identify the tests and data that would be needed before such a substitution could be justified. The review does not claim that bamboo-based absorbent cotton is currently a pharmacopoeial product. It considers (i) the production and classification of conventional surgical cotton, (ii) the botany, chemistry, physical properties and extraction of bamboo fibre, (iii) a feature-by-feature comparison with cotton, (iv) formulation and processing variables, (v) potential applications, (vi) advantages, limitations and safety issues, and (vii) the pharmacopoeial parameters for evaluation. Sources were identified from published reviews and research articles on bamboo fibre, natural-fibre wound dressings and pharmacopoeial requirements for absorbent cotton.

II. SURGICAL COTTON

A. Historical perspective

Raw cotton and cotton cloth have been used for centuries to absorb wound exudate and protect injuries. Industrial purification of cotton into 'absorbent' or 'surgical' cotton began in the nineteenth century, alongside antiseptic and aseptic surgical technique. It is now a pharmacopoeial-grade product manufactured under controlled conditions to be free of waxes, oils and other hydrophobic constituents that would impede absorption of blood, serum and exudate. Its continued use is partly explained by the long clinical familiarity of surgeons and nurses with its handling, and by the fact that it is cheap enough to be used as a disposable item.

B. Conversion of raw cotton to absorbent cotton

- Ginning: removal of seeds from the raw fibre.
- Scouring: removal of natural waxes and oils, often by alkali treatment.
- Bleaching: whitening and further purification, usually with hydrogen peroxide.
- Together these steps strip the natural coating, converting the fibre from water-repellent to highly absorbent.

After bleaching, the fibre is washed free of residual alkali and oxidant, dried, opened and carded into a web of loosely entangled fibres. The carded web is then rolled or packed, and, where a sterile product is intended, sterilised and sealed in protective packaging. Beyond medical use, cotton is used in textiles, bedding, paper (cotton linters), and as a source of cottonseed oil and animal feed.

C. Types of surgical cotton

- Absorbent cotton: highly purified, degreased; absorbs exudate and blood; used for dressings, swabs and wound cleaning.
- Non-absorbent cotton: retains some natural waxes and oils; used where high absorbency is not needed.
- Sterile surgical cotton: absorbent cotton sterilised and individually packed for direct use.
- Non-sterile surgical cotton: purified cotton supplied unsterilised, sterilised before use when required.
- Medicated/antiseptic cotton: impregnated with antiseptic or medicinal substances for specific applications.

D. Functional requirements of an absorbent wound-contact material

Wound dressings are generally expected to absorb exudate, protect against contamination, avoid shedding particles, cause no toxic or sensitising reaction and be removable without trauma [7]. Early work showed that a moist wound environment favours epithelial repair compared with a dry one [15], and this is the reason that dry absorbent cotton is

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normally used as a secondary or padding layer, or over a non-adherent contact layer, rather than as the sole dressing for every wound type. Any bamboo-based substitute would be judged against the same functional requirements, in addition to the compendial tests described in Section VIII.

III. BAMBOO AS A FIBRE RESOURCE

A. Botanical and agronomic overview

Bamboo belongs to the subfamily Bambusoideae of the family Poaceae and comprises over a thousand species across tropical, subtropical and temperate regions, with extensive stands in South and Southeast Asia [10,14]. Some species can grow more than a metre in a day, and culms reach harvestable maturity in three to five years. A grove regenerates from its rhizome system without annual replanting or tillage, tolerates drought comparatively well, can be grown on marginal or degraded land, and helps with soil stabilisation. These traits give bamboo a lighter footprint than cotton at the cultivation stage. Because the culm is a perennial structure, harvest is selective and the plantation is not cleared, which preserves soil cover and reduces erosion compared with annual row crops.

B. Chemical composition

Bamboo culm is made up mainly of cellulose, hemicellulose and lignin, with smaller amounts of extractives and ash [2,5]. Cellulose provides the structural backbone and hydrophilicity. Hemicellulose and lignin form the matrix binding cellulose microfibrils; lignin gives rigidity but must be largely removed to give a soft, flexible, absorbent fibre. Proportions vary with species, culm age and the part of the culm used, affecting yield and quality. By comparison, cotton seed hair is almost pure cellulose with a thin outer layer of wax and pectin, which is why a comparatively simple scouring and bleaching sequence is sufficient to make it absorbent. Bamboo therefore needs a more demanding purification route, and the residual lignin and hemicellulose content of the finished fibre is a critical quality attribute.

C. Physical and mechanical properties

Bamboo fibre has a fine diameter, a central lumen and a porous cross-section with micro-gaps and grooves along its length [2]. This structure underlies its rapid moisture uptake and transport (often described as moisture-wicking). Once processed, it also shows good strength and flexibility for its fineness and a soft handle, all desirable in a wound-contact material. The same hydrophilicity that gives rapid uptake, however, makes native bamboo fibre sensitive to moisture, with swelling, loss of dimensional stability and susceptibility to degradation reported in the engineering literature [2,5].

1) Mechanism of fluid uptake

Fluid uptake in a fibre mass occurs by three overlapping routes: adsorption of water onto the hydroxyl groups of cellulose, capillary movement of liquid through the spaces between fibres, and, for fibres with a lumen or surface grooves, capillary movement within the fibre itself. In scoured cotton, the first two routes dominate, and the twisted, ribbon-like collapsed lumen of mature fibre gives a bulky, resilient web. Bamboo fibre offers a larger proportion of micro-voids and surface grooves [2], which explains the rapid wicking seen in textiles, but a carded mass of short, straight fibres may pack more densely and hold less fluid per gram than a lofty cotton web. Absorbent capacity of the finished product thus depends as much on web structure (bulk density, fibre length, crimp) as on the chemistry of the fibre, and this should be borne in mind when interpreting results from textile studies.

D. Extraction methods

• Mechanical: crushing and combing the culm to separate fibre bundles. Avoids harsh chemicals but gives a stiffer, coarser fibre (bamboo linen when spun) with lower yield.

• Chemical: alkali (commonly sodium hydroxide) treatment of chips or pulp under controlled temperature and pressure to dissolve lignin and hemicellulose. Gives a softer, finer fibre, similar in concept to viscose production, but requires careful control and treatment of process chemicals.

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• Biological/enzymatic retting: microorganisms or enzymes degrade the pectin and lignin matrix while leaving cellulose largely intact. More environmentally benign but slower.
• Hybrid combinations of the above are also used.

For an absorbent cotton substitute, the extraction route directly affects softness, fibre length, purity and absorbency, and is therefore a key formulation variable. Reviews of extraction and treatment note that alkali treatment alters the cell wall and can change single-fibre tensile properties, so that the degree of delignification must be balanced against the strength and length that carding requires [2].

E. Types of bamboo fibre

TABLE I: TYPES OF BAMBOO FIBRE AND THEIR NOTABLE FEATURES

Type	Description and notable features
Natural (mechanical) fibre	Obtained mechanically; retains more natural structure; strong, biodegradable, moisture-absorbent.
Regenerated cellulose (viscose/rayon)	Cellulose extracted and regenerated into fibre; soft, smooth, highly absorbent.
Lyocell	Cellulose dissolved in a solvent and regenerated; soft, breathable, biodegradable; generally regarded as a more environmentally preferable regeneration process.
Bast fibre	From outer fibrous tissues; relatively good tensile strength; used in textiles and composites.
Microfibre	Very fine fibres with high surface area; useful in absorbent materials and textiles.
Pulp fibre	Bamboo converted to pulp, then processed into fibre.
Charcoal fibre	Bamboo charcoal particles incorporated in a fibre matrix; added adsorption and antimicrobial properties.

For a cotton-wool substitute the most relevant categories are the natural (mechanically or enzymatically processed) fibre, which keeps the native cellulose structure, and regenerated cellulose, which is soft and uniform but loses part of the original fibre architecture and, according to several authors, much of any intrinsic antimicrobial character [8,9].

IV. COMPARISON OF CONVENTIONAL COTTON AND BAMBOO FIBRE

TABLE II: COMPARISON OF CONVENTIONAL COTTON AND BAMBOO FIBRE

Feature	Conventional cotton	Bamboo fibre (viscose/rayon)
Source	Natural seed hairs of the cotton plant	Cellulose extracted from bamboo pulp
Texture and softness	Soft, breathable; can feel textured	Very soft, silky and smooth
Moisture management	Absorbs well but retains moisture and dries slowly	Superior wicking; dries quickly
Durability and structure	Strong; holds shape well	High tensile strength but prone to pilling or stretching if poorly cared for
Farming impact	High water and pesticide consumption	Fast-growing; minimal water, no pesticides
Processing impact	Standard textile milling and dyeing	Chemical-heavy processing (closed-loop systems mitigate this)
Cost	Generally lower; mass-produced	Generally higher due to processing and certification

The comparison shows a trade-off: bamboo is favourable at the farming stage, but its processing (particularly viscose-type routes) can offset that benefit unless closed-loop or lower-impact methods are used [8]. It should also be stressed that the data in Table II derive largely from textile applications. They describe fabrics rather than loose, carded fibre

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masses, and they do not substitute for compendial testing of a medical-grade product. A fair appraisal of bamboo as surgical cotton therefore has to separate three questions: whether the raw material is more sustainable, whether the finished fibre performs equivalently, and whether the overall production chain is genuinely less burdensome once chemical processing is included.

V. FORMULATION CONSIDERATIONS FOR BAMBOO-BASED SURGICAL COTTON

• Extraction method: determines residual lignin and hemicellulose, and so softness, colour and absorbency.
• Bleaching: must reach pharmacopoeial whiteness and purity without excessively degrading fibre length or tensile strength.
• Carding and web formation: must give a uniform, cohesive, bulky fibre mass comparable in handle and appearance to conventional absorbent cotton.
• Sterilisation: autoclaving or another validated method suited to cellulose, without harming physical integrity or absorbency.
The overall objective is a bamboo-based absorbent cotton that is visually, texturally and functionally comparable to pharmacopoeial-grade cotton wool.

A. Proposed process sequence

TABLE III: PROPOSED PROCESS SEQUENCE FOR BAMBOO-BASED SURGICAL COTTON

Stage	Purpose	Principal quality risk
Raw material selection	Choose species, culm age and growing site	Variability; soil-derived heavy metals
Delignification / extraction	Remove lignin and hemicellulose to free cellulose fibre	Residual lignin; fibre damage; process chemical residues
Washing and neutralisation	Remove alkali, dissolved matter and residues	Residual alkalinity; extractable matter
Bleaching	Achieve whiteness and purity	Loss of fibre length and strength; oxidant residues
Opening and carding	Form a uniform, cohesive, bulky web	Short fibre fraction; fibre shedding; neps
Packing and sterilisation	Provide a sterile or low-bioburden product	Loss of absorbency or integrity; recontamination

B. Critical quality attributes

Because bamboo fibre is shorter and more variable than the long staple of good-quality cotton, fibre length distribution is likely to be a decisive attribute. If too many short fibres are present, the carded web will lack cohesion, shed particulate matter and be unsuitable for wound contact. Residual lignin affects colour and may reduce wettability. Residual alkali or oxidant from processing affects the pH of the aqueous extract. Mineral content, carried over from the plant, affects ash. These interdependencies mean that the formulation cannot be optimised on a single parameter, and design-of-experiments approaches that vary extraction severity, bleaching conditions and carding settings together would be appropriate.

C. Sterilisation and packaging

Surgical cotton supplied as sterile must retain absorbency and strength after sterilisation. Moist-heat sterilisation is compatible with cellulose in principle, but repeated or prolonged cycles can reduce degree of polymerisation and cause yellowing, and any residual moisture left in a hydrophilic fibre mass can support microbial growth if the pack seal fails. Ethylene oxide and radiation methods are alternatives used for medical products, each with its own considerations (residual gas and aeration for the former, possible chain scission of cellulose for the latter). Whichever method is

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chosen, it has to be validated for the specific bamboo-derived material, and moisture content of the fibre before packing has to be controlled. Packaging should provide a microbial barrier and protect against moisture uptake during storage, since a bamboo fibre mass may be more hygroscopic than conventional cotton.

VI. POTENTIAL APPLICATIONS

- Absorbent layer in wound dressings for blood, exudate and other fluids.
- Absorbent material during and after surgery, subject to sterility and medical-device requirements.
- Cleaning and swabbing of wounds and surrounding skin.
- Absorbent wound-care pads.
- First-aid dressings after appropriate processing and sterilisation.
- Eco-friendly disposable wound-care products, given bamboo's renewability.
- Absorbent component in multilayer or composite wound-dressing systems.

The most plausible near-term role is as a component of composite or multilayer dressings rather than as a stand-alone replacement for sterile surgical cotton. Experimental work illustrates this: a biocomposite dressing combining sodium alginate, bamboo fibre cloth as mechanical reinforcement, and an antimicrobial extract was reported to have adequate physico-mechanical properties and antibacterial activity [1]. Such studies show that bamboo can be integrated into wound-care structures but do not address the requirements of loose absorbent cotton. Wider wound-dressing science also emphasises that dressing choice should be matched to wound type, exudate level and infection risk [7].

VII. ADVANTAGES AND LIMITATIONS

A. Advantages

- Rapidly renewable raw material and an alternative to cotton.
- High cellulose content suits cellulose-based absorbent materials.
- Biodegradable and potentially environmentally friendly.
- Good moisture absorption after appropriate processing; soft, lightweight material.

B. Disadvantages and limitations

- Can retain moisture if kept wet for long, may stick to wounds when fibres embed in dried exudate, and can shed loose fibres into the wound; not suitable as the sole material for every wound type.
- Sterile products need proper sterilisation and packaging.
- Natural fibre needs chemical or mechanical processing; processing chemicals may reduce environmental benefits.
- Variable quality depending on species, age, growing conditions and process; uniform length, thickness and strength are hard to achieve.
- Moisture uptake may affect strength and dimensional stability; untreated fibre may have lower durability.
- Higher processing cost than cotton in some cases.
- Few standardised methods and specifications for bamboo-based medical products compared with cotton.
- Marketing issues: some products sold as '100% natural bamboo' are in fact regenerated cellulose, raising labelling and 'greenwashing' concerns [4,8].

C. Heavy-metal safety

Bamboo can take up soil contaminants, including lead, cadmium, arsenic, mercury and chromium, through its extensive rhizome system and move some into stems, leaves and shoots. Studies of bamboo-growing soils, for example in Guangdong Province, China, have reported average lead levels above 70 mg/kg in several areas, above risk-screening thresholds. For a wound-contact product this makes raw-material sourcing and testing for heavy metals an important quality consideration, alongside ash content. Practical controls would include sourcing from plantations with

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documented soil analysis, specifying acceptance limits for elemental impurities in the raw culm and finished fibre, and verifying by validated analytical methods such as atomic absorption or inductively coupled plasma techniques.

D. Antimicrobial claims

The antimicrobial reputation of bamboo should be treated with caution. Laboratory work has examined the origin of the antibacterial property of bamboo and reported that activity is associated with the native plant material and extracts rather than being a guaranteed property of every bamboo-derived fibre [9]. Regeneration processes such as viscose production are generally thought to remove or greatly reduce such activity [8]. A surgical cotton substitute should therefore not be marketed as inherently antimicrobial unless this is demonstrated on the finished, sterilised product by standard microbiological methods.

E. Environmental and life-cycle considerations

The principal argument for bamboo is environmental, so it deserves critical examination rather than assumption. At the cultivation stage, bamboo's perennial habit, regrowth from rhizomes and low input requirement compare favourably with cotton, whose water footprint is large [6]. Bamboo is also a plant of substantial biomass productivity [10]. The picture changes at the processing stage. Dissolving bamboo into regenerated cellulose by viscose-type processes involves carbon disulphide and strong alkali, and effluent control is essential; lyocell-type processes using recoverable solvents are generally regarded as preferable [8]. Mechanical and enzymatic routes avoid most of these chemicals but give coarser fibre and lower yield, and may not reach the purity needed for medical use without further treatment.

A credible sustainability claim for a bamboo-based surgical cotton would therefore require a cradle-to-gate life-cycle assessment covering land use, water, energy, process chemicals, effluent treatment, transport and packaging, compared on an equal functional basis (for example per kilogram of sterile product meeting the same absorbency specification). End-of-life should also be considered. Both cotton and bamboo cellulose biodegrade, but contaminated medical waste is usually incinerated or autoclaved rather than composted, so biodegradability is of limited practical benefit for used surgical dressings, although it matters for unused material and packaging waste. Disposable products also raise a separate question of whether reductions in consumption, rather than substitution of raw material, would deliver larger environmental gains.

VIII. EVALUATION AGAINST PHARMACOPOEIAL STANDARDS

A bamboo-derived absorbent cotton should be tested against a standard cotton wool reference and the acceptance criteria of the relevant monograph (IP/BP/USP) [11–13]. Principal parameters:

- Water absorbency: sinking time and quantity of water absorbed per gram.
- Acidity or alkalinity of the aqueous extract.
- Ash content (inorganic and mineral residue).
- Fibre length, diameter and uniformity by microscopy.
- Tensile strength and handling characteristics of the carded mass.
- Sterility and microbial load after sterilisation.
- Foreign matter, immature or dead fibre and visible impurities.
- Preliminary biodegradability and, where feasible, qualitative screening of antimicrobial activity.

TABLE IV: PARAMETERS FOR EVALUATION AGAINST PHARMACOPOEIAL STANDARDS

Parameter	What it reveals	Bamboo-specific concern
Sinking time / water-holding capacity	Speed and capacity of fluid uptake	Residual lignin or incomplete purification may slow wetting
pH of aqueous extract	Residual acid, alkali or process chemicals	Carry-over of NaOH or bleaching agents

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Ash / residue on ignition	Mineral content	Plant-derived minerals; possible soil contaminants
Fibre length and diameter	Suitability for carding; shedding risk	Shorter, more variable fibre than cotton
Water-soluble and ether-soluble substances	Residual waxes, oils, finishes, extractables	Extractives from the plant; processing aids
Fluorescence / foreign matter	Contaminants, optical brighteners, impurities	Dyes or brighteners must not be used
Elemental impurities	Safety of a wound-contact material	Uptake of Pb, Cd, As, Hg, Cr by bamboo
Sterility / bioburden	Microbiological safety	Moisture-retentive fibre may support growth if packaging fails

Several of these tests are simple, inexpensive and can be performed in a student or small-laboratory setting, which makes a comparative screening study of bamboo-derived and conventional cotton feasible. Because the monographs are revised periodically, the current edition of the pharmacopoeia should always be consulted for test methods and limits rather than relying on summaries.

IX. CONCLUSION

Bamboo is a renewable, cellulose-rich fibre with a porous structure that suits absorbent applications, and it offers clear agronomic advantages over cotton. Its suitability as a surgical cotton substitute depends on processing choices, purity, heavy-metal safety and demonstrated compliance with pharmacopoeial standards. Systematic experimental evaluation against these standards is needed before bamboo-based absorbent cotton can be considered a viable eco-friendly alternative.

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