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Cotton Waste a Source of Sustainable Energy- A Review

Samar Gogari, Radha* and Niharika Sharma
School of Biological and Environmental Sciences,
Shoolini University of Biotechnology and Management Sciences, Solan (Himachal Pradesh), India.

(Corresponding author: Radha)*
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ABSTRACT: Approximately 25% of the fibre produced worldwide comes from cotton production. Although it is grown in around 80 nations, the United States, China and India continue to be the biggest producers, together making up more than half of the world's total. However, there are serious environmental issues associated with this large output. Cotton waste, comprising gin by-products and field wastes, amounts to millions of tons each year. Agricultural output is hampered by slow soil decomposition, also insect and disease problems are made worse by waste build-up. Cotton stalks and gin waste are perfect for producing renewable energy due to their lignocellulosic composition. Biofuels like ethanol, bio-oil, and fuel pellets are produced by processes including pyrolysis and fermentation, which can take the place of fossil fuels and lower carbon emissions. Cotton waste serves as a base material for producing high-value products, such as low-cost animal feed, substrates for mushroom cultivation, activated carbon for wastewater treatment, and bio-based building materials like particleboards. Research also shows that it can be used to synthesize enzymes and seal lagoons. Since using cotton waste not only reduces environmental issues but also promotes the circular economy by reducing dependency on non-renewable resources and increasing resource efficiency, this review highlights the conversion of numerous by-products from cotton waste. In order to boost product yields and economic viability, future research should concentrate on refining pre-treatment techniques, optimizing biomass conversion technologies, and investigating biotechnological developments.

Keywords: Cotton waste, Lignocellulosic biomass, Renewable energy, Biofuels, Agricultural residue management.

INTRODUCTION

Waste is increasingly being recognized as a valuable resource, leading to its transformation into various products that significantly benefit different industries. This paradigm shift is driven by the principles of the circular economy, which aims to minimize waste and make the most of resources. For instance, organic waste from the food industry can be converted into biogas through anaerobic digestion, which can then be used as a renewable energy source. Similarly, plastic waste can be reprocessed into new plastic products, reducing the demand for virgin materials. Industrial symbiosis plays a crucial role here, where the waste or by-products of one industry become the raw materials for another. For example, fly ash, a by-product of coal-fired power plants, can be used in the construction industry to produce concrete. Such practices not only reduce environmental pollution but also enhance resource efficiency and provide economic benefits. Consequently, this approach not only mitigates the environmental impact but also fosters sustainable development by creating new business opportunities and promoting green technologies (Vegad, 2017); Jani *et al*., 2020; Tongo, 2020; Chakraborty *et al*., 2020; Pandey *et al*., 2023). Similarly, Cotton is the most widely used natural fiber meeting the increasing demands of textile industry globally. Data from the FAO (2022) shows that global cotton production rose from roughly 41.9 million metric tons in 2018 to 45.4 million metric tons in 2019. Asian continent made a significant contribution to these figures, producing roughly 27.3 metric tons in 2018 and 29.5 metric tons in 2019. India was the biggest producer of cotton in 2018 and 2019, accounting for around 9.9 million metric tons in 2018 and 12.5 million metric tons in 2019. In 2022, annual world production of raw cotton was around $50 billion, while global trade in cotton fibre was at around $20 billion, according to UN estimates (UNCTAD, 2023). Cotton plant waste (CPW) and cotton gin waste (CGW) are the two main categories of waste cotton residues that are known (White *et al.*, 1996; Holt *et al.*, 2000; Rogers *et al.*, 2002). The residue that remains in the field after harvesting cotton is referred to as cotton plant trash. It is estimated that the annual production of cotton generates between 4700 and 5100 kgs of cotton stalk trash per hectare (Curtis *et al.*, 2003; Gilbert and Huhnke 2003). Cotton stalks are leftover residues that remain unused for now, yielding an average of 4.5 tons of dry matter per hectare annually (MALR, 2002). They are potential biomass sources for production of renewable energy (Gemtos and Tsiricoglou 1999). Stems are primarily composed of a well-structured wood framework with distinct wood rays and water-transporting channels (Brown and Ware, 1958; Gad *et al*., 1987). Stems have an average fiber length of 1.1 mm. Cotton stems are 10–20% wet at normal temperature. They weigh roughly 450 kg/m^3 in mass. About 25% of the substance is lignin, followed by 37.0% cellulose, 20.4% hemicellulose, 4% ash and 4% extractives (Fahmy *et al.*, 2000). The mean height is about 126 cm and mean diameter of the stalks is about 10.3 mm (Tayel *et al*., 1988). It was stated by El Bassam (1998), that the cotton stalks which are dried can be used as a fuel which is sustainable. Cotton stalks include cellulosic material that may be a valuable resource for the energy and industrial sectors following pyrolysis and gasification. Cotton stalks' chemical composition varies greatly depending on their origin, cultivar, growing environment, and harvesting technique (Agblevor *et al.*, 2003). Table 1 presents the details of cotton production worldwide, along with cotton waste generated.

Table 1: Cotton waste: characteristics and uses.

Attributes	Details	References
Types of cotton waste	— Cotton plant waste: Remnants left on field after harvesting. — Cotton gin waste: Waste produced during the cotton ginning process.	White *et al*., 1996; Holt *et al*., 2000; Rogers *et al*., 2002; Sharma and Chen 2008
Quantity of cotton stalk waste	5.2 to 5.6 tons per hectare per year.	Curtis *et al*., 2003; Gilbert and Huhnke 2003
	Average dry matter yield: 4.5 tons per hectare per year.	MALR, 2002
Potential use	Production of energy from biomass	Gemtos and Tsiricoglou 1999
Physical properties	— Moisture content: 10-20% (at room temperature). — Bulk density: 450 kg/m³. — Mean diameter: 10.3 mm. — Mean height: 1.26 m.	Tayel *et al*., 1988
Chemical composition	— Lignin: 25%. — Cellulose: 37.9%. — Hemicellulose: 20.4%. — Ash: 4%. — Extractives: 4%.	Fahmy *et al.*, 2000
Wood structure	Water-carrying vessels and prominent wood rays.	Brown and Ware 1958; Gad *et al*., 1987
Energy potential	Can be used as fuel. Suitable for pyrolysis and gasification for industrial applications.	El Bassam, 1998
Variation factors	Origin, cultivar, growing location, and harvest method.	Agblevor *et al*., 2003

CHARACTERISTICS AND COMPOSITION OF COTTON WASTE

After harvesting, stalks must be disposed of because boll weevils and other insects may use them as feeding and fruiting grounds (Silverstein *et al.*, 2007). Cotton gin waste is the term used to describe products from the ginning process, with the exception of seed and lint (Holt *et al.*, 2000); (Sharma and Chen, 2008). Additionally, a 218 kg cotton bale produces 68 to 91 kg of cotton gin waste and roughly 336 kg of seed (Rossi, 2006). According to Schacht and Lepori (1978); Thomasson (1990), they could be made up of leaves, mote, sticks, soil particles, burs, lint, and other plant components. According to reports, the bulk densities of fresh wet is 183.3 ±52.2 kg m^{-3} and dry CGW is and 210.2 ±59.9 kg m^{-3}, respectively (Agblevor *et al.*, 2006). Similar to cotton plant waste, CGW is composed primarily of cellulose, lignin and hemicellulose (Agblevor *et al.*, 2006). Table 2 gives the overview of cotton gin waste (CGW).

Table 2: Overview of cotton gin waste (CGW).

Category	Details	References
Definition	By-products (other than seed or lint) of the cotton ginning process.	Holt *et al*., 2000
Annual production (U.S.)	Approximately 2.25 million tons across the cotton belt.	
By-product yield (per bale)	About 336000 g of seed and 68 to 91 kg of cotton gin waste are produced from a 218 kg bale of cotton.	Rossi, 2006, Sharma and Chen 2008
Components of CGW	Consists of various plant parts such as twigs, burs, soil particles, leaves, mote, and cotton lint.	Schacht and Lepori 1978; Thomasson 1990; Sharma and Chen 2008
Bulk Density (fresh wet)	210.2 ±59.9 kg m³.	Agblevor *et al*., 2006
Bulk Density (dry)	183.3 ±52.2 kg m³.	
Composition	Primarily cellulose, hemicellulose, and lignin, similar to cotton plant waste.	

DISPOSAL CHALLENGES OF COTTON WASTE

Each bale of 226800 g of raw cotton lint produced during the process of ginning, about 50000 to 60000 g of cotton gin trash (CGT) is eliminated (Hamawand *et al.*, 2016). Currently, this cotton gin trash is a waste stream that ginners are having more and more trouble for disposal. The most frequent way to handle trash is to pile it up in big windrows. One of the most important methods for controlling soil organic carbon is to keep cotton waste on the farm (Terrapon-Pfaff, 2012). Area of land required for disposal of CGT increases every year each season. Large heaps of these residues are more likely to catch fire (Hamawand *et al.*, 2016). One of the most important methods for controlling soil organic carbon is to keep cotton waste on the farm. To preserve and enhance quality of soil and increase carbon sequestration, the Australian cotton industry advocates for the adoption of cotton-rotation crop sequences and minimum tillage (Hulugalle and Scott 2008). Direct reapplication of CGT to soils growing cotton is strictly prohibited due to the anticipated risk to farm health posed due to soil-borne pathogens and chemical residues found in some fresh gin trash samples, like verticillium wilt (McMahon, 2012; Hamawand *et al.*, 2016). Ismail *et al.* (2011), studied the energy used for cotton gins in Australia. The benchmark power usage for the ginning operation was determined to be between 44 and 66 kWh, while the drying process needed either 2.27 to 5.61 L of LPG gas or 0.74 to 3.90 m^3 of natural gas per bale. By recycling a waste supply, CGT biomass conversion to electricity would lower operating and waste management expenses (Stucley *et al*., 2004; Multer *et al*., 2010).

Fresh gin trash samples may contain soil-borne pathogens, like verticillium wilt, and chemical residues, which pose a significant threat to farm hygiene. As a result, directly applying cotton gin trash to cotton-growing soils is strictly prohibited (Hadar *et al*., 1993). Incineration, incorporation into the soil and land filling are the traditional operations used for cotton residual waste disposal (Thomasson, 1990; OWR, 1995). Incineration is no longer an option for disposing of cotton waste since the updated Federal Clean Air Act limits the amount of particulate matter that can be released into the atmosphere (Fuller *et al.*, 1997). Tipping is quite expensive, so landfilling is not a cost-effective solution (Agblevor *et al*., 2006). Incorporating cotton residual waste directly into soils requires considerable effort. Besides being ineffective in soil amending, it can degrade structure of soil as well as increase the risk of soil erosion (White *et al.*, 1996). As an alternative, using cotton waste to produce high-value products like ethanol and industrial chemicals overcomes disposal problems, turns financial obligations into income, lowers the use of fossil fuels, and lessens negative environmental effects (Akpinar *et al*., 2007). Numerous experiments were conducted for converting cotton waste into energy or goods with added value, such as construction materials, animal feed, soil amendments, and adsorbents. There is a lack of knowledge and information evaluating the total potential of using cotton waste, despite the fact that several research report on the different products that may be made from it. The aim of this review is to summarize the vast amount of information on transforming cotton waste into value-added products and bioenergy into a concise overview. Sharma and Chen (2008), estimated that upon harvest, 5.2 to 5.6 tonnes of cotton stalks remain in the field per hectare.

POTENTIAL UTILIZATION OF COTTON WASTE

When properly treated, cotton waste can be used as a raw materials for the generation of renewable sources of energy like bioethanol, pyrolysis gas, fuel pellets, biogas, liquid fuel/bio-oil, etc. Its energy value ranges from 18600000 to 20900000 J kg^{-1} (OWR, 1995). The lignocellulose in cotton stalks and cotton gin waste makes them ideal for generating renewable energy. Processes like pyrolysis and fermentation are used to create biofuels, such as ethanol, bio-oil, and fuel pellets, which can replace fossil fuels and reduce carbon emissions. High-value items including inexpensive animal feed, substrates for growing mushrooms, activated carbon for treating wastewater, and bio-based building materials like particleboards are all made from cotton waste. Additionally, studies indicate that it might be utilized to synthesize enzymes and seal lagoons. Fig.

1 provides a visual summary of these applications and Table 3 summarizes all the applications of cotton waste.

A. Renewable energy production

(i) Fuel pellets. The manufacturing of fuel pellets can be a lucrative way to use cotton gin by-products to make money, according to raw material economic analysis, operating, as well as shipping costs (Holt *et al*., 2004). Scientists of USDA-ARS have developed the patented COBY (Cotton By-product) process in Texas for value addition to cotton waste. This process aims to create various end-products from the same base raw material. Fuel pellet is one of those products, which provide a sustainable, clean, and affordable alternative for heating at home (Holt *et al*., 2004). In COBY process cotton waste is treated with gelatinized starch and other additives, followed by heat, grinding, and/or blending and pressure treatments (Holt and Laird 2001). Additional methods, such as carbonization and briquette formation, are used to convert cotton biomass especially stalks into fuel pellets. In another study, raw cotton stalks were first shredded and then carbonized in the kilns. After carbonization, these cotton stalks were sun-dried, hammer mill was used for grinding and these ground material were briquetted in an agglomeration machine. Proximate analysis showed that the briquettes had a calorific value of 20900000 J kg^{-1} (Abasaeed, 1992). In a different experiment, cotton waste was ground in a hand-operated press and combined with pecan shell to form briquettes. Compared to briquettes generated from paper waste, those made from cotton residue waste had a somewhat low durability, a higher ash content, and a faster flame-out time (Coates, 2000). According to a research carried out by Sumner *et al.* (1981), 45 to 64% of the energy from biomass, measured by oxygen bomb calorimeter tests was heat accessible. This was contingent upon the residue's burning properties.

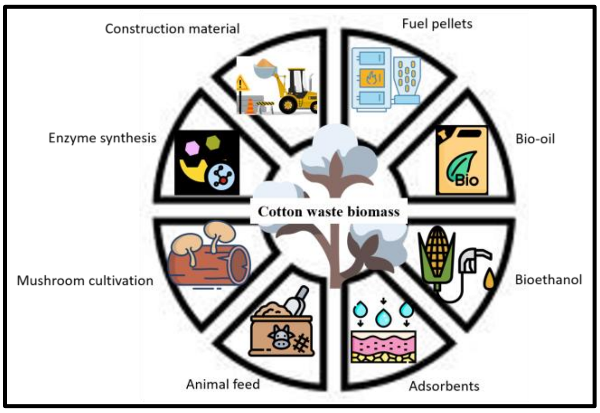

Fig. 1. Cotton stalk re-utilization for producing bio-based products.

(ii) Pyrolysis. Pyrolysis liquefaction is an efficient method for converting biomass into energy (Weiming *et al.*, 2005). Pyrolysis is a process that breaks down biological materials at high temperatures (between 475 and 478°C) in the absence of oxygen, producing charcoal, bio-oil and gas (Demirbas, 1998). The resulting oil or gas can be transformed in to valuable alternative fuels, industrial gases and chemical products (Chen *et al.*, 2003). The University of Arizona developed a combined harvesting and liquefaction process for converting cotton residues into liquid fuel (White *et al.*, 1996). Equipment such as uprooter-shredder-mulchers, guayule diggers/cutters, cotton stalk pullers, or wind-row inverters were used to harvest the cotton stalks. The harvested stalks were then liquefied in an extruder-feeder system to produce high-quality crude wood oil. This liquefaction process results in liquid fuel (bio-oil) with a heating value of approximately 37200000 J kg^{-1}, which is twice of energy content of residual biomass (White *et al.*, 1996). Cotton stalk pyrolysis was studied at 850°C in a fixed-bed reactor. On a biomass basis of kJ kg^{-1}, the ultimate pyrolysis products were 17% char, 5% tar, 20% water, and 58% gas. The gas had a calorific value of 14,000 KJ Nm^{-3} and was composed of 60% flammable gases (CO and H_2) (Chen *et al.*, 2003).

B. Bioethanol production

According to an analysis of biomass composition, the percentage of carbohydrates (mostly cellulose and hemicellulose) in cotton gin waste is roughly 35% and in cotton stalks it is 49%, (Agblevor *et al.*, 2006; Silverstein *et al.*, 2007), Galactan, arabinan, and mannan are found in very minor levels in cotton waste, whereas glucan and xylan make up 80% to 90% of the total carbohydrates. This is similar to other agricultural wastes. Potential of cotton gin waste as a source for bioethanol production was investigated by Researchers at Texas Tech University (Beck and Clements, 1982). A method for turning cellulose and hemicellulose into furfural and ethanol, respectively, was developed. *Trichoderma longibrachiatum* immobilized cellulases were used to hydrolyze cellulose, and baker's yeast was used to ferment the resulting hydrolysate. Additionally, CGW was transformed into bioethanol by fermentation using ethanologenic *E. coli* KO_{11}, steam explosion, and enzymatic hydrolysis. The effectiveness of enzymatic hydrolysis increased from 42% to 67% due to steam explosion. The maximum amount of ethanol produced was 83% of the theoretical amount (Jeoh and Agblevor, 2001). To enhance cotton stalks' saccharification, Silverstein *et al.* (2007), examined effectiveness for different chemical pre-treatment techniques and pre-treatment settings to enhance the saccharification of cotton stalks. When compared to dilute H_2SO_4, H_2O_2 and ozone pre-treatments, NaOH pre-treatment produced the best cellulose conversion and 65.63% of maximum delignification (Hamawand *et al.*, 2016). Cotton stalks pre-treated with sodium hydroxide (2% NaOH, 60min, 121°C/103.4 kPa) had a saccharification rate of 60.8% as opposed to 23.85% with acid and 49.82% with H_2O_2, respectively. It was found that CGW can provide a yield of 143.1 L of ethanol per 1000 kg of gin waste (Jeoh, 1998; Hamawand *et al.*, 2016).

Table 3: Overview of potential uses of Cotton stalks.

Potential uses	Description	References
Fuel pellets	Fuel pellet production from cotton gin by-products is cost-effective; COBY process developed by USDA-ARS for multiple end-products.	Holt and Laird 2001; Holt *et al.*, 2004
	Carbonized cotton stalk briquettes have a calorific value of 20900000 J kg^{-1}	Abasaeed, 1992; Sharma and Chen 2008
	Briquettes from cotton waste had higher ash content and lower durability than paper briquettes.	Coates, 2000
	Heat availability during burning was 45–64% of total biomass energy.	Sumner *et al.*, 1981
Pyrolysis	Converts biomass to gas, charcoal, and bio-oil under non-oxidative conditions; bio-oil heating value is 37.2 MJ kg^{-1}.	Demirbas, 1998; Chen *et al.*, 2003; Sharma and Chen 2008; Hamawand *et al.*, 2016
	Pyrolysis of cotton stalks produced 58% gas, 20% water, 17% char and 5% tar.	
Bioethanol production	Cotton waste contains 35%–49% carbohydrates; used for bioethanol production with yields up to 83%.	Sharma and Chen 2008; Hamawand *et al.*, 2016
	Sodium hydroxide pre-treatment achieved highest delignification (65.63%) and saccharification (60.8%).	Jeoh 1998; Silverstein *et al.*, 2007
	Ethanol yield from CGW was 143.1 L ton^{-1}.	
Adsorbents	Activated carbon from cotton waste showed high dye and heavy metal adsorption efficiency (>89%).	Kadirvelu *et al.*, 2003; Attia *et al.*, 2004; Thangamani *et al.*, 2007
Animal feed	Cotton residues provide winter feed for ruminants; similar performance compared to Bermuda grass hay.	Conner and Richardson 1987; Rossi, 2006
Mushroom cultivation	Cotton waste supports high-yield cultivation of mushrooms like *Pleurotus* spp., leveraging its lignocellulosic properties.	Chang, 1983; Fasidi, 1996; Tan and Wahab 1997; Philippoussis *et al.*, 2001
Enzyme synthesis	Cotton waste serves as a low-cost substrate for cellulase production and mushroom growth.	El-Nasser *et al.*, 1997; Tan and Wahab 1997
Construction material	Cotton stalks used to make particleboards meet industrial standards; CGW tested as a lagoon sealant.	Smith and Tollner 1999; Guler and Ozen 2004

C. Adsorbents

A study by Attia *et al.* (2004) found that carbons produced from cotton stalks using zinc chloride and steam activation exhibit a higher surface area, significant total pore size, and excellent dye adsorption capacity. It was examined whether activated carbon from treating silk cotton hulls with strong sulphuric acid might be used to remove dye from textile effluent (Thangamani *et al.*, 2007). Activated carbon derived from silk cotton hulls can efficiently remove pollutants such as dyes and heavy metals (e.g., mercury II) from aqueous solutions, achieving a removal efficiency exceeding 89% within a short period (Kadirvelu *et al.*, 2003).

D. Animal feed

Due to a significantly high cellulosic content, the waste from cotton can be fed to grazing livestock (Conner and Richardson 1987). Feed costs can also be significantly decreased by using cotton leftovers, such as cotton stalks, cottonseed hull, linters and gin waste as a winter feed (Rossi, 2006). Performance of cows grazing on cotton stalks was compared with that of cows fed on coastal Bermuda grass hay by researchers at University of Georgia. Cows which were fed hay, mowed cotton stalks and standing cotton stalks gained 56, 32 and 55 pounds in total weight after 30 days, respectively. This suggests that cotton stalks are suitable for this use (Rossi, 2006).

E. Mushroom cultivation

Philippoussis *et al.* (2001), grown wild and commercial strains of *Agrocybe aegerita, Pleurotus ostreatus, Volvariella volvacea, Pleurotus eryngii* and *Pleurotus pulmonarius,* using cotton waste residues. The growth of mushrooms on lignocellulosic wastes is an economical way to reduce waste and recycle organic waste (Tan and Wahab 1997). Main constituents of lignocellulosic matter utilized as substrate for mushroom development are lignin, cellulose, and hemicellulose (Fasidi, 1996; Hamawand *et al.*, 2016). The hydrolytic and oxidative enzymes needed to break down these compounds in to small molecules for absorption are produced by fungi that are cultivated on the substrate (Tan and Wahab 1997). Fasidi (1996), examined the fructification of *Volvariella esculenta* on agriculture residues, like cotton waste, rice bran, and corn chaff. Cotton waste produced the largest and most consistent mushroom yield as compared to other wastes, indicated by its higher cellulose content and compactness upon wetness. Fructification begun 13 days after germinating on cotton waste. When the hydrolytic and oxidative enzymes required to break down these components into smaller molecules are produced by fungi growing on the substrate, this process is known as fructification (Chang, 1983).

F. Enzyme synthesis

Cotton stalks and other agricultural waste are abundant resources that can be used as low-cost fermentation media to create valuable enzymes (El-Nasser *et al.*, 1997). Tan and Wahab (1997) supported the growth of *Pleurotus sajorcaju*, an edible fungus, using sawdust and cotton waste as substrates. The mycelial plug was added to cotton waste that had been soaked in liquid culture media. After that, the medium was incubated for 60 days at 25°C under stationary conditions. For generating cellulase, cotton waste was a more effective substrate and inducer than sawdust.

G. Construction material

Cotton stalks can be pressed at a high temperature to create building materials like particleboards. Guler and Ozen (2004), used urea formaldehyde resin and ammonium chloride as a binding agent and hardener while pressing chopped cotton stalks at 150°C, 2.4 to 2.6 MPa, for 6 minutes. The resulting particleboards demonstrated engineering qualities (internal bond strength, bending strength, and water adsorption) that could satisfy industrial requirements. To keep groundwater clean, anaerobic lagoons need to be sealed at the sides and bottom. Using sealants like clay, bentonite, soda ash, or artificial can add to the capital cost (Smith *et al.*, 1999). As an alternative, the application of cotton waste as a lagoon bottom sealant has also been studied. CGW was utilized as a lagoon sealant by Smith and Tollner (1999), who packed it with soil and gravel layers and then kneaded and compacted it to create the sealant. Because the resulting hydraulic conducting capacity (2.2×10^{-6} cm s^{-1}) was lower than the sealant without cotton gin waste, it can be employed as a biological sealant for waste treatment lagoons, even though its effectiveness is still being investigated.

CONCLUSIONS

Cotton waste, a significant by-product of cotton farming and processing, poses environmental challenges such as soil degradation, greenhouse gas emissions, and pest proliferation due to improper disposal methods like landfilling and incineration. However, it also presents economic opportunities. Cotton stalks and gin waste, with their lignocellulosic composition, can be used to produce renewable biofuels such as ethanol, bio-oil, and fuel pellets, reducing dependence on fossil fuels and lowering carbon emissions. Furthermore, cotton waste can be transformed into valuable products like activated carbon for wastewater treatment, animal feed, mushroom cultivation substrates, and bio-based construction materials, such as particleboards. These by-products also serve as a substrate for enzyme production, supporting industrial processes. The sustainable utilization of cotton waste addresses environmental concerns by reducing landfill use, mitigating soil erosion, and lowering greenhouse gas emissions. Future research should focus on improving biomass conversion technologies like pyrolysis, fermentation, and gasification, as well as developing cost-effective pre-treatment methods to enhance product yield and quality. Advancements in biotechnology, such as genetically engineered microorganisms, could optimize enzymatic hydrolysis and fermentation processes for bioethanol production. Integrating cotton waste into circular economy models would further boost its scalability and promote sustainable practices. Policymaking, focused on encouraging sustainable agricultural practices and incentivizing bioenergy projects, will be crucial in unlocking the full potential of cotton waste. By transforming these residues into renewable energy and high-value products, cotton waste can shift from being an environmental burden to a driver of economic growth and sustainability, aligning with global efforts to foster a greener, more resource-efficient future.

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