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From Cotton Waste to Clean Energy: Cotton-Stalk-Derived Carbon for Sustainable Energy Storage

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Abstract
The growing use of renewable energy has created a need for affordable and sustainable energy-storage materials. At the same time, agriculture produces large quantities of waste that are often burned or discarded. This paper explores the possibility of converting cotton stalk, an agricultural residue, into carbon materials for energy-storage applications. Cotton stalk contains cellulose, hemicellulose and lignin, making it a suitable carbon-rich material. Through controlled heating and activation, it can be converted into porous carbon with properties suitable for supercapacitors. Previous studies have demonstrated good energy-storage performance from cotton-stalk-derived carbon, while recent research has also explored its use in sodium-ion batteries. The significance of this approach extends beyond energy storage: it provides a possible link between agriculture, waste management and clean-energy technology. Instead of treating cotton stalk only as waste, it can be considered a potential raw material for value-added materials. This paper discusses the basic conversion process, applications, environmental benefits and challenges of this approach. It proposes agricultural-waste-derived carbon as a promising complementary material for sustainable energy-storage technologies.

Keywords: *Cotton stalk, agricultural waste, energy storage, supercapacitor, biomass carbon, clean energy, sustainable materials, circular economy.*

1. Introduction

The world is increasingly adopting renewable energy sources such as solar and wind power. However, these sources do not produce electricity continuously. Solar energy, for example, is available mainly during daylight hours, while electricity demand continues throughout the day. Energy-storage technologies are therefore essential for making renewable energy more reliable.

Batteries are currently the most widely used energy-storage technology. Supercapacitors are another important option, particularly for applications requiring rapid charging, rapid energy delivery and a large number of charge–discharge cycles.

The development of these technologies requires materials that are not only efficient but also affordable, easily available and environmentally responsible.

At the same time, agriculture produces significant amounts of plant residue. Cotton stalk is one such residue left after cotton harvesting. It is often treated as agricultural waste and may be burned, discarded or used for low-value applications.

This creates an interesting opportunity: **Can agricultural waste be converted into a useful material for clean-energy storage?**

This paper examines the potential of converting cotton stalk into carbon materials for supercapacitors and other energy-storage applications.

2. Literature Review

2.1 Biomass-Derived Carbon

Biomass contains naturally occurring carbon-rich components. When plant material is heated under controlled conditions, it can be converted into carbon. Further treatment can create pores and increase the surface area of the material.

Porous carbon is particularly useful in supercapacitors because a large surface area allows greater interaction between the electrode and the electrolyte. Agricultural residues are therefore being investigated as inexpensive sources of carbon for energy-storage devices.

This approach also provides an environmental advantage because a waste material can be converted into a useful product instead of being discarded.

2.2 Cotton Stalk as a Carbon Source

Cotton stalk mainly contains cellulose, hemicellulose and lignin. These components make it suitable as a precursor for carbon materials.

Research has demonstrated that cotton stalks can be converted into porous carbon for supercapacitors. Tian et al. (2021), for example, developed porous carbon from waste cotton

stalks and used it in an all-solid supercapacitor. The reported device achieved an energy density of 12.5 Wh/kg at a power density of 900 W/kg.

Another study reported a specific capacitance of approximately 338 F/g for activated carbon prepared from cotton stalk. These studies demonstrate that cotton stalk can be transformed from an agricultural residue into a functional energy-storage material.

3. Research Work

3.1 Proposed Material Pathway

The basic concept discussed in this paper is:

Cotton harvesting → Cotton stalk waste → Controlled heating → Carbon material → Activation → Energy-storage electrode

After harvesting, cotton stalk can be collected and processed under controlled conditions to produce carbon. Further treatment can increase its porosity and improve its suitability for energy storage.

The important idea is that the natural carbon-containing structure of the plant is used as the starting point for producing a functional material.

3.2 Why Supercapacitors?

Supercapacitors differ from conventional batteries. They can generally charge and discharge much faster and can withstand a very large number of cycles. Their main limitation is their lower energy density compared with many batteries.

Porous carbon is useful for supercapacitors because it provides a large surface for charge storage. Cotton-stalk-derived carbon can therefore provide a low-cost alternative source of electrode material.

The reported performance of cotton-stalk-derived carbon demonstrates that agricultural residues can be used to produce materials with useful electrochemical properties.

3.3 From Waste to Resource

The most important aspect of this approach is not simply the performance of the carbon. It is the change in how agricultural waste is viewed.

A conventional pathway can be represented as: **Agriculture → Crop → Residue → Disposal**

The proposed pathway is: **Agriculture → Crop → Residue → Carbon material → Energy-storage device**

This is an example of **waste valorisation**, where a material with low economic value is converted into a higher-value product.

It also supports the idea of a circular economy, in which materials are kept useful for longer rather than being immediately discarded.

4. Potential for Other Energy-Storage Technologies

The potential of cotton-stalk-derived carbon is not limited to supercapacitors.

Recent research has investigated cotton-stalk-derived hard carbon for **sodium-ion batteries**. Sodium-ion batteries are attracting interest because sodium is widely available and may reduce dependence on some materials used in conventional lithium-ion batteries. A 2026 study reported that chemically treated cotton-stalk-derived hard carbon achieved a discharge capacity of 330.2 mAh/g at 0.1 C and retained 81.9% of its capacity after 1,000 cycles at 2 C under the reported test conditions.

This research suggests that the same agricultural residue can potentially be converted into different forms of carbon for different energy-storage technologies. Therefore, cotton stalk could become part of a broader biomass-based materials platform rather than being limited to a single application.

5. Environmental Benefits and Challenges

The environmental value of this approach comes from converting an agricultural residue into a useful material.

If cotton stalk that would otherwise be burned or discarded can be converted into energy-storage materials, two problems can potentially be addressed at the same time:

1. Agricultural-waste management.
2. Demand for sustainable energy-storage materials.

There are, however, important challenges.
First, processing requires energy. Carbonization involves heating, and excessive energy consumption could reduce the environmental advantage of the process.
Second, some activation methods use chemicals. Safer chemicals, chemical recovery and cleaner processing methods should therefore be investigated.
Third, biomass is not completely uniform. Cotton stalk can vary according to cultivation conditions, soil, climate and variety. This may affect the properties of the final carbon.
Finally, laboratory performance does not guarantee commercial success. Large-scale production must be economical, safe and environmentally responsible.
Future studies should therefore consider the complete life cycle of the material, from collection of cotton stalk to production, use and eventual recycling.

6. Future Scope

The next stage of research should focus on making the entire process more sustainable.
Important areas include:

- Developing lower-energy carbonisation methods.
- Using safer and recyclable activation processes.
- Improving the performance of biomass-derived carbon.
- Investigating its use in sodium-ion batteries.
- Establishing small processing units near agricultural areas.
- Conducting life-cycle assessments to compare biomass carbon with conventional carbon materials.
- Developing recycling methods for the final energy-storage devices.

Local processing could be particularly interesting. Instead of transporting low-value agricultural waste over long distances, cotton stalk could potentially be processed close to where it is produced.
A future model could therefore be:
Farm → Cotton stalk → Local processing → Carbon material → Energy storage
Such a system could create additional value from agricultural residues while supporting the development of local clean-energy technologies.

7. Conclusion

The transition to clean energy requires not only renewable sources of electricity but also sustainable materials for storing that energy. Cotton stalk provides an interesting example of how agricultural waste can become a useful resource for this purpose. Research has shown that cotton stalk can be converted into porous carbon with useful properties for supercapacitors. Recent research has also explored cotton-stalk-derived hard carbon for sodium-ion batteries.
The larger importance of this approach lies in its circular-economy potential. Instead of viewing cotton stalk only as waste, it can be considered a potential raw material for advanced energy-storage materials.
The concept can be summarised simply:
Cotton waste → Carbon material → Energy storage → Clean-energy applications
Cotton-stalk-derived carbon will not replace every conventional energy-storage material. However, it could become a useful complementary material, particularly in regions where agricultural residues are readily available. The future of sustainable energy may therefore depend not only on discovering completely new materials, but also on **finding new and valuable uses for materials that we currently treat as waste.**

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