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PRODUCTION OF SUPERCAPACITORS FROM LOCAL MATERIALS FOR ELECTROCHEMICAL ENERGY STORAGE DEVICES

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Abstract. This article analyzes the issue of producing supercapacitors based on local raw materials, which stand out among electrochemical energy storage systems due to their rapid charging, high power density, and extremely long cycle life.
Keywords: supercapacitor, electrochemical energy storage, local raw materials, activated carbon, biomass, electrode material, EDLC, porous carbon, cotton stalk, fruit pits, Uzbekistan.

Introduction. The most acute problem of modern energy systems is not the generation of electricity, but its management. As renewable energy sources such as solar and wind become more widespread, tasks related to grid stability, frequency control, short-term reserve power, peak load compensation, and pulse energy transmission are becoming far more complex than before. In this context, supercapacitors are no longer merely laboratory objects, but practical devices used in electric transport, industrial automation, renewable energy systems, medical equipment, telecommunications, railways, and microgrids. Their main strength lies in the fact that they can be charged within seconds, deliver high power, withstand millions of cycles, and operate more stably than batteries under repeated rapid charge-discharge conditions.

The ratios of lignin, cellulose, and hemicellulose, ash content, volatile matter fraction, density, the ability to form microcracks, and the capacity to create a porous architecture when activated with KOH or H_3PO_4 are all crucial factors determining electrode quality. International research in the field of supercapacitors shows that biomass-based carbons attract considerable attention as electrode materials because they are inexpensive, environmentally sustainable, and capable of forming highly developed porous structures. For example, in some experimental results, biomass-based carbons have shown a specific capacitance of up to 479.23 F/g. Naturally, this value cannot be transferred directly to the raw materials of Uzbekistan, but the principle is clear: if the correct carbonization and activation regime is selected, competitive electrode materials can also be obtained from local resources.

Another aspect of the topic is the reduction of dependence on imports. High-quality activated carbon, specialized electrode reagents, separators, and electrode technologies are often imported from abroad. Under such circumstances, not only the production of the final product but also the gradual localization of the entire technological chain becomes a strategic task. If local activated carbon production from cotton stalks or fruit pits is established, at least the basic electrode component can be supplied from internal resources. This yields a double benefit: first, waste is transformed into an economic resource; second, part of the imported material is replaced. In addition, there is an opportunity to optimize carbon materials for local conditions. For instance, while a high-power industrial supercapacitor may require one type of porous structure, a low-power sensor system may need another. Imported ready-made materials do not always provide such subtle adaptability.

Literature Review. In the global literature on supercapacitors, three main directions are clearly visible: the first direction is high-surface-area porous carbons for electric double-layer capacitors; the second is transition metal oxides or hydroxides providing pseudocapacitive effects; the third is hybrid systems, namely combinations of carbon and redox-active components. In mass commercial production, the most mature technology is EDLC, in which the main focus is on maximizing electrode surface area, creating open transport channels for ion diffusion, and reducing internal resistance.

Biomass-based carbon materials have become one of the most actively studied classes for improving this balance. The reason is simple: biomass naturally possesses a multilevel structure, and during carbonization and chemical activation it tends to form micro- and mesoporous architectures. In an analytical study published in PMC, supercapacitor properties were tested in carbons obtained from banana stems, corn cobs, starch, and other biomass materials, and a KOH-activated sample demonstrated a specific capacitance of up to 479.23 F/g. Of course, this is a laboratory-level result, but its main scientific signal is important: the type of biomass, the activation reagent, and the thermal regime dramatically affect the electrode properties. Therefore, in working with local raw materials, there is no “one universal recipe”; each precursor requires its own thermochemical route.

Methodology. This article is not an experimental laboratory report, but a scientific paper based on comparative analysis and a technological model. Within the scope of the analysis, three groups of sources were combined: first, international institutional sources on energy storage systems; second, scientific articles on biomass-based supercapacitor electrodes; and third, the works of Uzbek researchers on local raw materials and carbon sorbents. On this basis, five criteria for selecting local materials for supercapacitors were developed: stable availability of raw materials, carbon yield, ash content, potential for forming porous structures, and localization value. Then the technological chain was modeled as follows: sorting the raw materials → drying → grinding → carbonization → chemical or physical activation → washing and neutralization → drying → preparation of electrode paste → coating onto a current collector → drying and pressing → assembling into a coin-type or pouch-type cell → electrochemical testing using CV, GCD, and EIS methods. This methodology provides both a real experimental plan and an initial technical direction for industrial transition. The following table presents the comparative selection model proposed within the framework of this article.

Type of local raw material	**Availability level**	**Expected quality of carbon framework**	**Potential advantage**	**Main risk**	**Evaluation for supercapacitors**
Cotton stalk	Very high	Medium–high	Cheap, large volume, abundant agricultural waste	Ash content and non-uniform composition	Very promising
Apricot/peach pit	Medium	High	Dense lignin structure, relatively strong carbon framework	Seasonality, logistics	Promising
Walnut/almond shell	Medium	High	Good tendency to form porous structures	Raw material volume may be regionally limited	Very promising

Type of local raw material	**Availability level**	**Expected quality of carbon framework**	**Potential advantage**	**Main risk**	**Evaluation for supercapacitors**
Reed	High	Medium	Large biomass flow, low harvesting cost	High mineral additives and moisture	Promising
Fruit and vegetable waste	High	Medium	Reduces ecological waste problem	Variable composition, difficult standardization	Promising with targeted sorting

As can be seen from the table, the greatest advantages in raw material selection belong to cotton stalk and hard nutshell-type biomass. The former is strong in terms of volume, while the latter is favorable in terms of material quality. For rapid industrialization, a compromise must be found between quantity and quality.

Analysis and Results. The results of the analysis show that, in selecting local materials for supercapacitors, the single most important factor is not surface area alone. If a material contains only micropores, ion transport slows down; if mesopores dominate, the surface reserve decreases. The most optimal path is to create a balanced system of micro- and mesopores. Chemical activation, especially with KOH, often provides a high surface area, but the consumption of reagents, washing stages, and corrosion risks are high. Activation with H_3PO_4 can provide a softer porous structure in some biomass materials, but residual phosphorus-containing groups may alter electrochemical behavior. Physical activation is environmentally softer, but usually requires more energy and time. Therefore, the technological solution must be selected not only by "the best result" but by "the most optimal economic and ecological balance."

According to the analytical model, a two-stage path appears to be the most logical under the conditions of Uzbekistan. The first stage is the production of inexpensive, stable, and reproducible activated carbon based on local biomass. The second stage is the modification of this carbon, for example by enriching it with nitrogen or oxygen functional groups, increasing the degree of graphitization, introducing conductive additives, or forming a hybrid system. Pure carbon-based EDLC provides a simple and reliable solution; hybridization may increase capacitance, but it can also complicate cycle stability and cost. Therefore, as an initial industrial approach, a symmetric EDLC based on locally produced activated carbon is advisable. This is the simplest path, with low risk and easy testability.

The economic logic of supercapacitor production is also quite clear. In DOE estimates, the base storage block cost for a 1 MW, 45-second EDLC system in 2025 is given as $19,200/kWh. This figure looks very high in terms of energy units and explains why supercapacitors are not designed for long-term storage. However, this figure should not be misinterpreted. A supercapacitor is not a "kWh device," but a "kW device." It solves the problem of power, not energy. If a device can deliver high power within seconds and operate for a million cycles, then its economic efficiency should be assessed not by kWh, but by fast-response services and cycle number. Without understanding this point, comparing a supercapacitor and a battery using the same criteria leads to incorrect conclusions.

The analysis of local materials showed that cotton stalk is the strongest candidate for Uzbekistan in terms of raw material volume. However, it is not the easiest from the technological point of view. Cotton residues may contain mineral impurities and compositional non-uniformity, which can increase ash content and negatively affect internal resistance.

As a conceptual result, the following scientific-technological pathway is proposed: 1) mapping raw material flows by regions; 2) optimizing carbonization and activation regimes based on DOE data and global experience; 3) creating a passport for each carbon sample according to BET, SEM, Raman, XRD, EIS, CV, and GCD indicators; 4) assembling a symmetric two-electrode EDLC prototype; 5) conducting accelerated cycling tests for 5,000–10,000 cycles; 6) selecting target applications for industrial automation, solar inverters, and small transport systems. If the sequence "first material, then device, then application" is not maintained, the project will remain in the laboratory. The greatest risk here is jumping directly from materials science to a market product. A step-by-step transition is required, not a leap.

Discussion. The idea of producing supercapacitors from local raw materials is attractive, but several hard questions must be answered before it can be implemented. The first question is: what is the goal — publishing a scientific article or creating a working technological platform? If the goal is only a publication, several laboratory results in the range of 300–500 F/g may be sufficient. If the goal is a product, then besides capacitance, such factors as cycle stability, ESR, electrode mass loading, binder selection, separator compatibility, electrolyte safety, and serial reproducibility become decisive. The second question is: which market segment is being targeted? The requirements for consumer electronics differ greatly from those for industrial reserve power modules. The third question is: where does the economic advantage of the product come from? Not from the cheapness of raw materials alone.

Thus, the claim of "green technology" is not automatic; it can only be proven by LCA and techno-economic analysis. In future research on biomass-based supercapacitor materials under the conditions of Uzbekistan, not only electrochemical results but also water consumption, reagent recycling, the cost of one kilogram of electrode material, waste coefficient, and carbon footprint must be taken into account. Only then will the work acquire real scientific and practical value.

Conclusion. The analysis presented in this article shows that the production of supercapacitors from local materials for electrochemical energy storage devices is not merely an interesting scientific topic for Uzbekistan, but a strategic technological direction. There are three main reasons for this. First, global energy systems increasingly require flexible, fast, and high-power storage solutions. Supercapacitors are particularly strong in this segment: they charge quickly, possess an extremely long cycle life, demonstrate efficiency of around 92%, and can work very effectively alongside batteries in tasks operating in the range of seconds to minutes. Second, Uzbekistan possesses sufficient agricultural and organic resources that can be used as electrode materials for such devices, including cotton stalks, walnut and almond shells, apricot and peach pits, reeds, and other agro-organic residues. Third, converting local waste into high-value carbon materials provides environmental, economic, and industrial benefits simultaneously.

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