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Review Article

Roles of solid waste derived carbon for supercapacitor applications: A review

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ABSTRACT
Our future is being jeopardized by the widespread use of solid waste in our modern society, which has detrimental effects on nature, the environment, and human well-being. The excessive generation of solid waste can be attributed to our actions. As the human population grows rapidly, the volume of solid waste increases daily. To achieve more favorable outcomes in managing solid waste, a viable solution is to convert it into valuable carbon-based nanomaterials (CNMs), including carbon quantum dots (CQDs), carbon nanotubes (CNT), and graphene, which can also be employed in energy storage devices. Carbon-based electrode materials, because of their expansive area on the surface and permeable design, hold great potential for supercapacitor applications. This article examines the impact of these materials on the electrochemical properties of supercapacitors, assesses their prospects, and explores the scope of their application. Furthermore, this article delves into the ongoing challenges and future advancements required for enhancing energy storage efficiency in devices.

1. Introduction

Non-renewable sources have served as the primary energy supply for numerous years, leading to various environmental issues that impact the well-being of the general public. In light of these prevailing challenges, scientists have shifted their focus towards renewable energy sources, such as solar energy (sunlight), wind power, and even waste heat from industries, all of which offer the advantage of generating energy without CO_2 emissions. However, the resolution of this problem requires the establishment of adequate energy storage infrastructure. In addition to batteries [1] and fuel cells, supercapacitors (SCs) have emerged as promising solutions due to their appealing features, including high power density and rapid charging and discharging capabilities [2-4].

In the quest for sustainable development, harnessing energy from renewable and clean sources has emerged as the most promising solution to address energy crises and environmental issues. Thanks to rapid advancements in materials science, a wide range of sustainable energy sources have been extensively studied. These include wind energy, solar power, ocean energy, biomass energy, geothermal energy, and hydropower, as depicted in (Figure 1A).

Of all the energy sources, solar energy emerges as one of the most significant, offering various forms and substituting traditional fossil fuels with renewable energy sources. It possesses multiple advantages, such as abundant availability, eco-friendliness, ease of storage, and high accessibility [5]. Unlike conventional non-renewable energy sources, solar energy is evenly distributed worldwide, facilitating the establishment of efficient energy facilities even within distant regions (depicted in Figure 1B).

In spite of its benefits, solar power presents certain ecological limitations that hinder its extensive and long-term utilization [6]. One of these limitations is its low power density. Solar energy is inherently unpredictable due to the transition between day and night, as well as its susceptibility to weather conditions (Figure 1B). The low energy density and limited power output pose significant obstacles to practically utilizing solar energy.

Direct storing of solar energy is a challenging task. Typically, solar power is initially converted into new power formats before being stored [7-8]. There are a few successful methods for converting and storing energy derived from sunlight, examples include solar-to-thermal [9-10], solar-to-biomass, solar-to-chemical, and solar-to-electrochemical conversions for energy storage [11-12]. Among these approaches, solar-to-electrochemical conversion holds several distinct advantages. Undoubtedly, the advancement of converting and storing solar energy into electrochemical energy represents a highly promising development for large-scale, long-term, and diversified energy applications.

An established method for achieving solar-to-electrochemical energy conversion and storage involves the integration of solar cells with electrochemical energy storage devices (EES) [13-15]. This combined energy conversion and storage system comprises two key elements: a solar cell that captures energy and an EES device designed to store the gathered energy, such as a rechargeable battery or a supercapacitor (SC). Within this hybrid apparatus, the solar cell's role is to capture solar energy and transform it into electricity, which is then electrochemically stored in the EES component. This comprehensive sequence of actions is denoted as the "photo charging" mechanism. Conversely, the stored energy is discharged when needed to power external devices through the EES component (illustrated in Figure 1C).

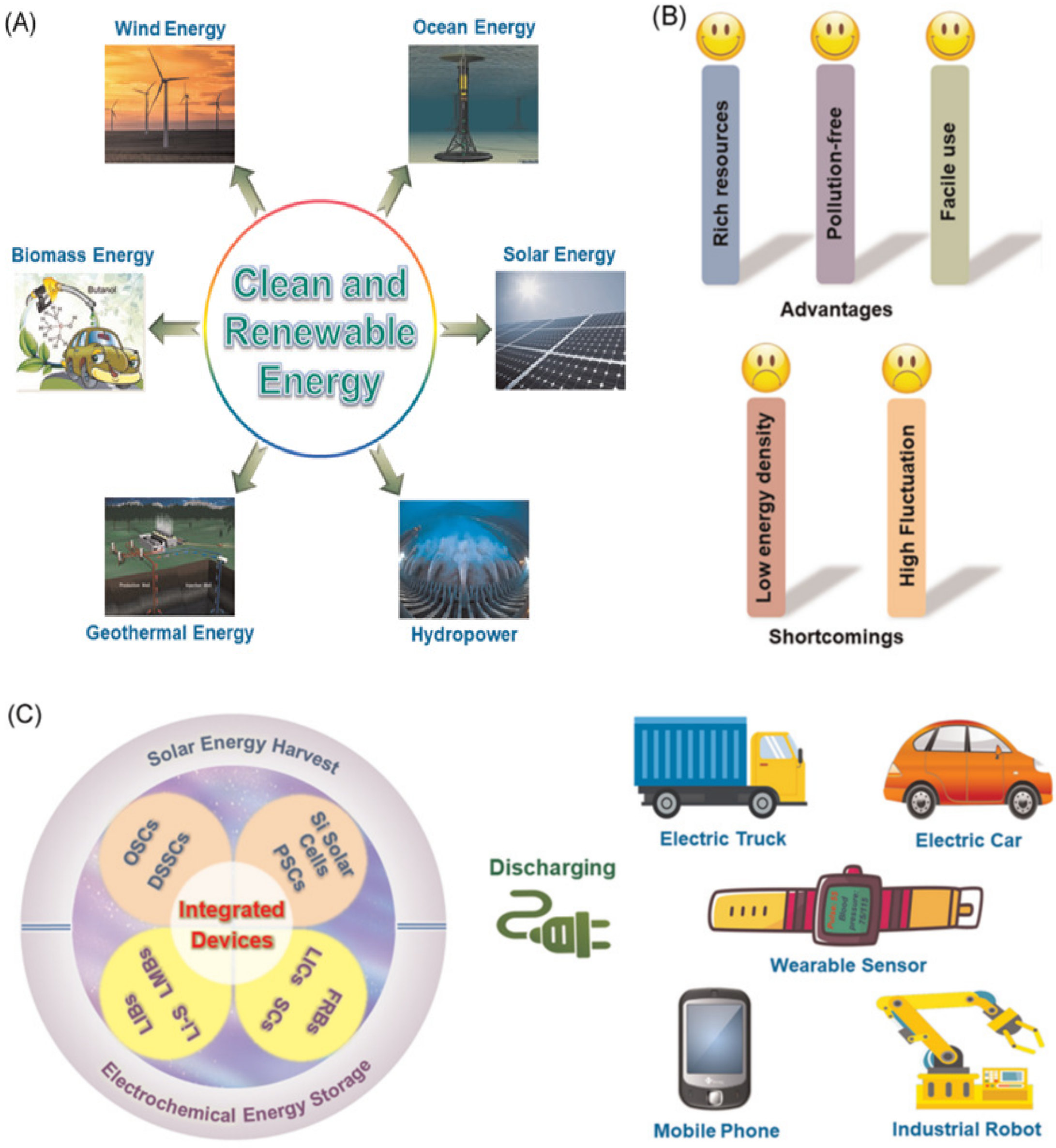

Figure 1: (A) Various sources of renewable and environmentally friendly energy [16]. (B) Benefits and limitations associated with solar energy [16]. (C): A visual representation outlining the roles and potential uses of integrated systems [16].

2. Solid waste as a universal problem

Solid waste has arisen as a global predicament because of its detrimental influence on the ecosystem and human health. The excessive production of various types of solid waste, encompassing plastic waste, agricultural waste, chemical waste, paper waste, machinery waste, and electronic waste, can be attributed to the continuous growth of the population and its overall needs. It has become an exceedingly perilous issue that simultaneously affects human health and the environment. Solid waste is associated with numerous diseases, including cancer, skin ailments, respiratory infections, birth defects, and reproductive disorders. Furthermore, inadequate waste management significantly contributes to ocean pollution, river blockages, floods, and harm to wildlife that inadvertently ingests the debris, thereby disrupting ecological balance.

Table 1 illustrates the contribution of different regions of the world to plastic waste generation, while Figure 2 showcases the distribution of solid waste in India. Solid waste has become an extensive predicament with the potential to manifest anywhere, regardless of its local context. To enhance our understanding of the issue at hand, general solid waste can be classified into two categories: carbon-based and non-carbon-based solid waste. Figure 3 presents the hierarchy of diverse solid waste from a global standpoint. The vertical representation of the ongoing prevalence of solid waste, along with its distribution, underscores the urgency for sustainable management practices.

Table 1: The contribution of different areas worldwide in the generation of waste plastic [17, 18].

S. no.	Province	Plastic production in %
1.	China	23
2.	Europe	21
3.	Rest Asia	20
4.	Middle east Africa	7
5.	Latin America	5
6.	Japan	5
7.	CIS	3
8.	NAFA	20
9.	**USA**	**16**

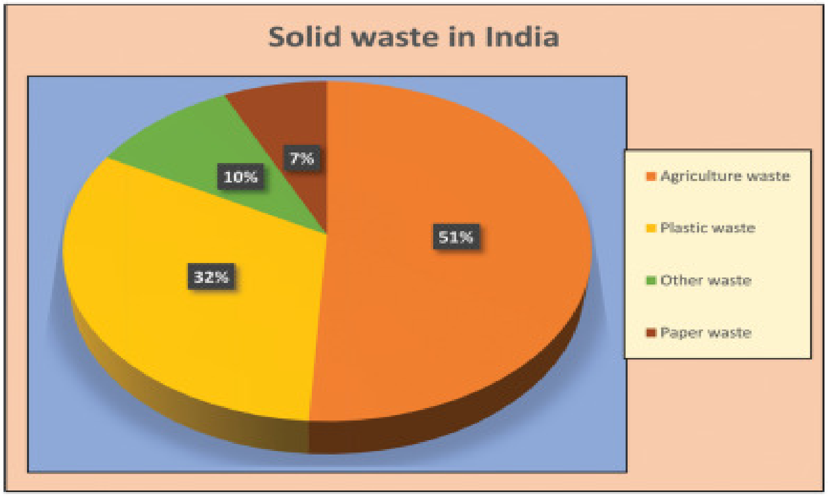

Figure 2: The distribution of solid waste in India [19, 20].

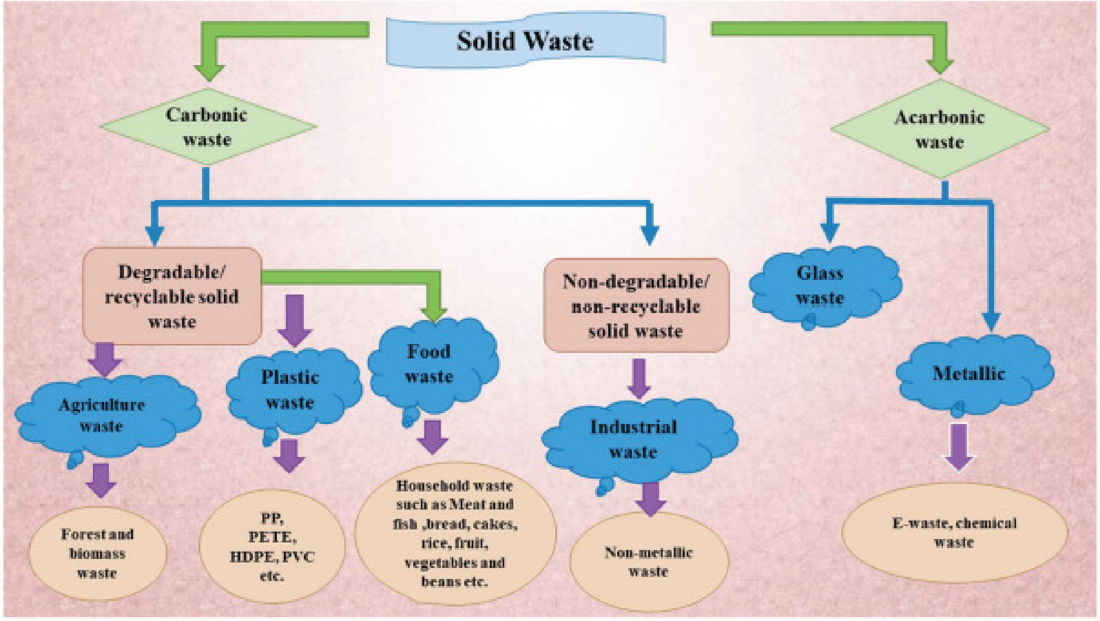

Figure 3: Schematic illustration of the distributions of various solid wastes [20].

3. Solid-waste derived CNMs in supercapacitors

The properties of carbon nanomaterials (CNMs) derived from solid waste are heavily influenced by the raw materials and experimental conditions employed. These CNMs demonstrate exceptional electrical conductivity and possess an unusually large surface area, making them valuable components for manufacturing supercapacitor devices. Supercapacitors are electrochemical energy storage devices designed to rapidly store and release energy, enabling them to handle high currents for short durations. Consequently, they find widespread application in electric vehicles, uninterruptible power supplies (UPS), and IT systems for memory backups, among other uses. Figure 4 illustrates the representation of various types of supercapacitors utilizing carbon nanomaterials (CNMs).

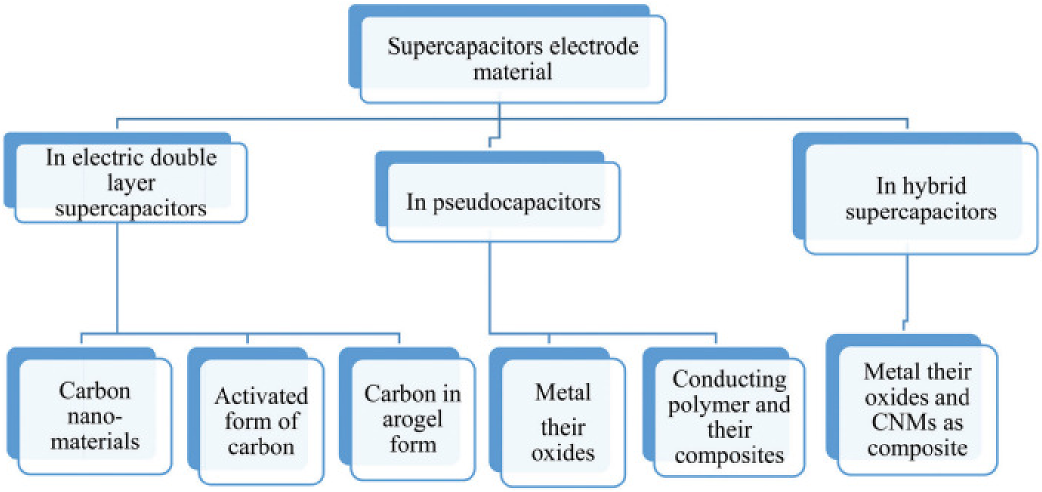

Figure 4: Hierarchy displaying the use of CNMs in various types of supercapacitors [20].

4. Future prospective and challenges

To provide support to analysts for future analyses, it is essential to consider several key factors at this stage. The primary factor to consider is the cost of producing activated carbon. It is crucial to adopt a method of activating carbon obtained from biomass that requires the least amount of energy throughout the entire process. Another important aspect to consider is the selection of biomass sources. It is advisable to choose affordable biowaste sources that are abundant and rich in carbon content to facilitate large-scale production. Experts have suggested that using the majority of these biowaste materials for energy storage can meet future energy demands since they are regularly produced in large quantities.

Care must be taken during biomass charcoal activation to prevent the release of unwanted gases such as NO_2 and SO_2 into the environment, which can contribute to climate pollution and other harmful effects. Additionally, the energy density of the electric double-layer capacitor (EDLC) is finite. However, this can be improved by enhancing the permeability of biomass-derived carbon, thereby increasing the surface area of the electrolyte particles. Another approach is to create composites with pseudo-capacitor materials.

It is important for research efforts to extend beyond research centers and be accessible at the mechanical and business levels as well. By optimizing conditions such as pyrolysis temperature, activation time, and activating agents, biomass should be treated according to the specific application's desired physical properties and surface chemistry. This comprehensive approach ensures that the biomass is tailored to meet the requirements of a particular application.

5. Conclusions

The accumulation of various types of solid waste has reached a critical point where we can now manage these wastes according to their appropriate applications. Nanotechnology has emerged as a significant achievement, bridging the gap between materials science and the human world. This technology not only offers solutions to ecological challenges but also establishes a harmonious balance between science and humanity. Due to the unique carbon content present in different solid waste materials, they can be transformed into carbon nanomaterials (CNMs).

The power sector's current focus lies in the development of sustainable energy sources. Extensive research efforts have been dedicated to harnessing wind and sunlight for the creation of ideal and efficient power systems. However, the intermittent nature of these renewable sources necessitates the design of energy storage devices that enhance reliability and reduce costs for future utilization. Activated carbon (AC) has shown promise as an electricity storage material. However, producing AC using expensive and hazardous metal-organic frameworks (MOFs) imposes challenges in terms of cost and consistency. As a solution, researchers have explored the use of AC derived from various waste sources, not only addressing the issue of waste disposal but also reducing the overall process costs. Additionally, with the abundance of organic waste generated daily, it has the potential to serve as an alternative energy source, replacing fossil fuels.

The use of AC in supercapacitor applications offers advantages over other carbon-based materials such as carbon nanotubes (CNTs), graphene, and carbon aerogels that have been previously investigated. The efficiency of AC is influenced by factors such as the arrangement and design of the source material, the specific preparation methods employed, and the surface functionality. These aspects highlight the importance of optimizing the surface area of the electrodes, as well as the number and size of pores in the starting material, to enhance their operational effectiveness.

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