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Scalable Manufacturing Techniques for Activated Charcoal-Based Electrodes in Commercial Battery Applications: A Concise Review

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***Abstract*:** *Extensive research into alternate battery electrode materials has been spurred by the need for sustainable energy storage options. Because of its affordability, availability, and eco-friendliness, activated charcoal has become a highly promising option. Nonetheless, a significant barrier to the commercial implementation of activated charcoal-based electrodes is the scalability of the manufacturing processes. An extensive summary of scalable production methods for activated charcoal-based electrodes used in commercial battery applications is given in this review paper. We go through an aspect of electrode production techniques, such as binder selection, electrode assembly, and physical and chemical activation processes. We also investigate how manufacturing characteristics like porosity, surface area, and shape affect electrode performance. Additionally, we highlight recent advancements and innovative approaches to address scalability issues and optimize electrode production for large-scale manufacturing. Through this review, we aim to provide insights into the current state-of-the-art techniques, challenges, and future directions in the scalable manufacturing of activated charcoal-based electrodes for commercial battery applications.*

Keywords: activated charcoal, electrode manufacturing, scalability, sustainable batteries, energy storage, electrode performance.

1. INTRODUCTION

The global demand for sustainable energy storage solutions has witnessed unprecedented growth in recent years, driven by the increasing adoption of renewable energy sources and the electrification of various sectors, including transportation and grid storage (Larcher & Tarascon, 2015). There is an urgent need to develop effective, affordable, and environmentally acceptable energy storage technologies to help the shift to a low-carbon future as traditional fossil fuel-based energy sources come under scrutiny for their effects on the environment and their limited supply.

. Central to the advancement of energy storage systems are batteries, which play a crucial role in storing and delivering electricity on demand.

According to Schmidt-Rohr (2018), a battery is a device that has the capacity to convert chemical energy that has been stored into electrical energy, which may be used to power electronic devices. This device has two terminals: the cathode, which is positively charged, and the anode, which is negatively charged.

An electrolyte acts as an energy-conducting medium between the two terminals (Schmidt-Rohr, 2018). Primary batteries and secondary batteries are the two different types of batteries (Guarnieri, 2022).

1.1 **Battery type**

1.1.1 Primary battery

Primary batteries are electrochemical cells designed for a single-use discharge, providing power for a variety of applications ranging from everyday electronics to specialized military and medical devices. These batteries capitalize on the energy stored in the chemical bonds of their active materials, which are not intended to be regenerated by recharging. (Blomgren & Hunter,2000).

Figure 1. Examples of primary battery (Blomgren & Hunter,2000)

A zinc-carbon battery, also known as a Leclanché cell, is a type of primary battery that generates electrical energy through a chemical reaction involving zinc and manganese dioxide. It consists of a zinc anode, a manganese dioxide cathode, and a carbon rod immersed in an electrolyte solution of ammonium chloride.

During discharge, zinc metal oxidizes at the anode, releasing electrons and forming zinc ions (Zn^{2+}). These electrons flow through an external circuit, generating electrical current. Meanwhile, manganese dioxide at the cathode reduces, accepting electrons and forming manganese oxide (Mn_2O_3) and water (H_2O).

The ammonium chloride electrolyte facilitates ion transport between the electrodes, maintaining charge neutrality. However, they have limited capacity and are susceptible to voltage drops and leakage during discharge, making them less suitable for high-demand applications compared to more advanced battery chemistries like alkaline or lithium-ion. Despite their drawbacks, zinc-carbon batteries remain popular for their affordability and widespread availability in consumer electronics (Qian *et al*, 2020).

As opposed to the acidic electrolytes used in conventional zinc-carbon batteries, alkaline batteries use an alkaline electrolyte, usually potassium hydroxide, as its primary battery. In comparison to zinc-carbon batteries, they are renowned for having a higher energy density and a longer shelf life.

The components of an alkaline battery are an alkaline electrolyte, a manganese dioxide cathode, and a zinc anode. Zinc metal oxidizes at the anode during discharge, releasing electrons and producing hydrogen ions (H^+) and zinc oxide (Fe_2O_3). Electrical current is produced as these electrons move through an external circuit. In the meantime, water and manganese oxide (MnO_2) are formed at the cathode as manganese dioxide reduces and accepts electrons. The alkaline electrolyte, usually potassium hydroxide (KOH), preserves charge neutrality and promotes ion transport between the electrodes.

Alkaline batteries are frequently found in a variety of gadgets., including portable electronics, toys, remote controls, and flashlights, due to their higher energy density and longer-lasting performance compared to zinc-carbon batteries. They are also a better option for high-demand applications since they are less likely to leak and experience voltage dips during discharge. Despite being more expensive than zinc-carbon batteries, alkaline batteries offer superior performance and reliability, making them a popular choice for consumer electronics and everyday use. (Karpinski *et al*, 2000).

Lithium primary batteries, often referred to as lithium-metal batteries, are a form primary battery known for their optimal energy potential and long shelf life. They utilize lithium as the anode material, which allows for higher voltage and energy density compared to other types of batteries.

A lithium primary battery typically consists of a lithium metal anode, a cathode made of materials such as manganese dioxide, sulfur dioxide, or thionyl chloride, and an electrolyte solution that facilitates ion transport between the electrodes. During discharge, lithium metal oxidizes at the anode, releasing lithium ions (Li^+) and electrons. These electrons flow through an external circuit, generating electrical current. Meanwhile, the cathode material undergoes reduction, accepting electrons and forming stable compounds. The electrolyte serves as a medium for lithium ion transport between the electrodes, maintaining charge neutrality.

Lithium primary batteries are renowned for their high level of energy density, which allow them to provide long-lasting power for number of applications, including medical devices, remote sensors, and backup power supplies.

They are also with a relatively low self-discharge rate, which contributes to their long shelf life. However, lithium primary batteries are non-rechargeable and must be disposed of properly after use. Additionally, they can be sensitive to overcharging, over-

discharging, and high temperatures, which may pose safety risks if not handled correctly. Despite these limitations, lithium primary batteries remain a popular choice for applications that require high energy density and reliable performance. (Amereller & Whittingham,2004).

Table 1. Typical examples and applications of primary batteries (Jayasayee, *et al*, 2021)

S/No.	Type	Application
1	Alkaline zinc manganese dioxide	Battery saver, portable CD player, digital camera.
2	Zinc silver oxide	Submarines, watches, hearing aids, pagers.
3	Zinc carbon	Table watches, remote controller, electronic equipment, radios, torches, flashlights, toys.
4	Zinc chloride	Calculator, remote controllers, clocks, recorders.
5	Lithium manganese dioxide	Test instruments, cameras, watches.
6	Zinc oxygen	Pagers, hearing aids.
7	Zinc mercury oxide	Calculators, hearing aids, pagers

1.1.2 Secondary battery

Rechargeable batteries, also referred to as secondary batteries, are a kind of battery that can be repeatedly charged and drained, enabling repeated use. Secondary batteries have a longer lifespan and are more environmentally beneficial in the long run since they can be recharged and used again, unlike primary batteries, which are made for one-time use.

They store and release electrical energy through reversible electrochemical reactions. An electrolyte solution separates the two electrodes, which are usually an anode and a cathode. In order to force electrons to go from the cathode to the anode during charging, a voltage is applied across the battery terminals by means of an external power source.

This process drives a reversible chemical reaction that stores energy in the battery. During discharge, the stored energy is released as electrons flow back from the anode to the cathode, generating electrical current.

There are several types of secondary batteries, each with its own unique chemistry and characteristics. Common examples include lithium-ion batteries, nickel-metal hydride (NiMH) batteries, and lead-acid batteries.

These batteries vary in terms of cycle life, energy density and performance characteristics, allowing them to be used in a wide range of applications, from consumer electronics to electric vehicles and grid energy storage (Nishi, 2001), (Guarnieri, 2022).

Table 2. Typical examples and applications of secondary batteries (Guarnieri, 2022)

S/No.	Type	Application
1	Lithium ion polymer	Portable media player, power banks, mobile phones, laptops, electric vehicles, tablets, electronic cigarette, wireless controller for video games.
2	Lithium ion	Locomotive, cameras, clocks, portable electronics, electric vehicles, wrist watches, digital diaries, stop watches, iPod, aerospace application.
3	Nickel Metal Hybrid	Laptop, mobile phones, robots, fuel cell, water activated batteries, flash lights, camcorders, T.V, hybrid electric vehicles.
4	Nickel cadmium	Cell phones, camcorders, computer instruments, power tools, toys, emergency lightings, flash light.
5	Nickel Iron	Mining equipment, off grid power supplies, backup power supply
6	Alkaline rechargeable	Video recorders, MP3 players, portable radios, cameras, cordless devices, hand held games.
7	Lead acid	Remote station, robots, portable emergency lights, UPS, ignition systems of automobiles, electric motors, backup power supplies, lawn mowers, wheel chairs, communication base station.

2. Role of Electrode Materials

Batteries comprise several key components, including the electrodes, electrolytes, and separators. Among these, electrodes serve as the active sites for electrochemical reactions during charge and discharge cycles. The selection and choice of electrode materials significantly influences the performance, energy density, cycle life, and cost-effectiveness of batteries (Wang *et al*, 2017).
Conventional electrode materials have been widely used but are linked to resource restrictions, performance limitations, and environmental concerns. Examples of these materials are graphite for lithium-ion batteries and lead dioxide for lead-acid batteries (Mancini et al, 2011).

2.1 Active Materials

Active materials constitute the primary electrochemical components of battery electrodes, undergoing reversible redox reactions during charge and discharge cycles. These materials encompass a diverse range of compounds, including transition metal oxides (e.g., lithium cobalt oxide, nickel manganese cobalt oxide), sulfides (e.g., iron sulfide, tin sulfide), and phosphates (e.g., lithium iron phosphate) (Chaouachi *et al*, 2021) (Inoue, 2012). Each active material exhibits unique electrochemical properties, such as specific capacity, voltage profile, and cycling stability, which dictate its suitability for different battery chemistries and applications (Zhang *et al*, 2020).

$$\textit{Active Material (oxidized)} + e^- \rightarrow \textit{Active Material (reduced)}$$

This equation represents the reduction of the oxidized form of the active material during discharge, where it gains electrons to become reduced. Conversely, during charge, the reduced form of the active material undergoes oxidation:

$$\textit{Active Material (reduced)} \rightarrow \textit{Active Material (oxidized)} + e^-$$

These redox reactions are fundamental to the operation of batteries, where the active material acts as the host for reversible ion intercalation or conversion reactions, allowing for the storage and release of electrical energy.

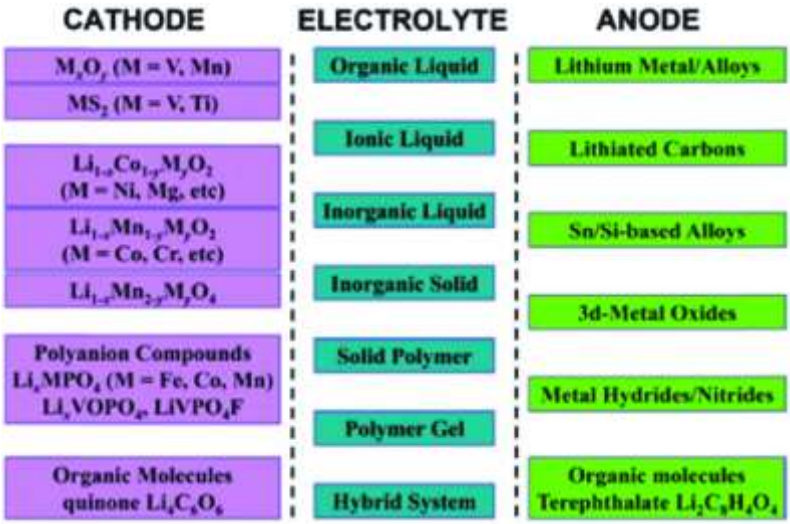

Figure 2. Electrochemical species of a battery system (Zhang *et al*, 2020)

For specific examples involving transition metal oxides, sulfides, and phosphates mentioned in the statement:

Transition Metal Oxides:

Metal Oxide (e.g., $LiCoO_2$) $+Li^+ + e^- \rightleftharpoons LiCoO_2(Li)$

Sulfides:

Iron Sulfide (FeS_2) $+ 2Li^+ + 2e^- \rightleftharpoons Fe + Li_2S$

Phosphates:

$LiFePO_4 + Li^+ + e^- \rightleftharpoons FePO_4 + Li_2O$

2.2 Conductive Additives

Conductive additives play a crucial role in facilitating electron transport within the electrode matrix, enhancing electrode conductivity, and improving overall battery performance (Deng *et al*, 2021), (Zhang *et al*, 2010). Commonly used conductive additives include carbon-based materials such as graphite, carbon black, and carbon nanotubes. These additives form conductive pathways throughout the electrode structure, enabling efficient electron transfer between active material particles and current collectors. Additionally, conductive additives help mitigate issues such as electrode polarization and improve the rate capability of batteries. (Zhang *et al*, 2010), (Marinho *et al*, 2012)

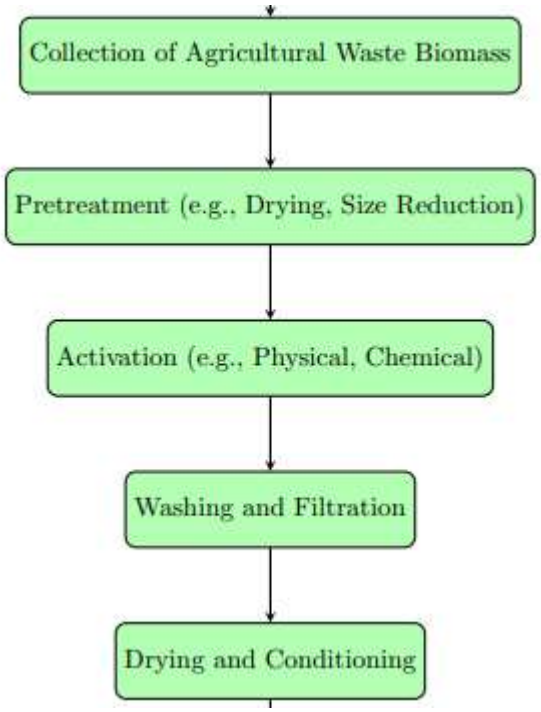

Figure 3. Carbon activation from agro waste biomass

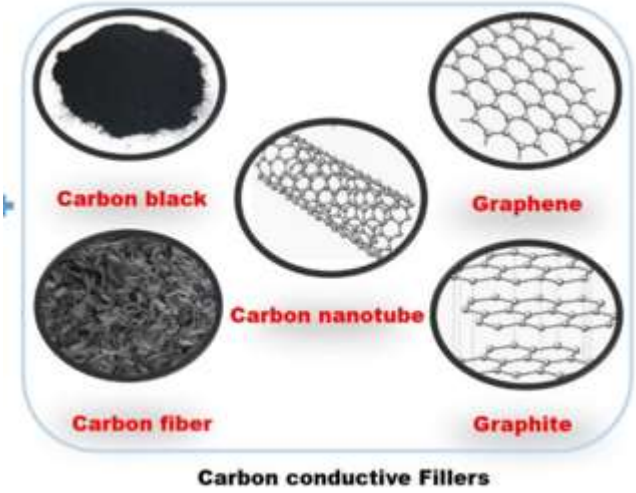

Figure 4. Basic forms of activated charcoal (Zhang *et al*, 2010)

2.3 *Binder Materials*

Binder materials are essential components of electrode formulations, serving to bind active materials and conductive additives together, as well as adhere them to the current collector substrate. Binders contribute to electrode integrity (Chen et al,2013), mechanical strength (Zou & Manthiram 2020), and flexibility (Zhang *et al*, 2015), thereby ensuring the structural stability of the electrode during cycling. Various binder materials, including polymeric binders (e.g., polyvinylidene fluoride, carboxymethyl cellulose) and aqueous binders (e.g., sodium carboxymethyl cellulose, styrene-butadiene rubber), are utilized based on their compatibility with electrode materials, processing requirements, and performance objectives. (Tong *et al*, 2020), (Rezvani *et al*, 2018).

3. Properties and Requirements of Electrode Materials

3.1 Electrochemical Properties

The electrochemical properties of electrode materials, including specific capacity (Ma *et al*,2016), voltage (Yu *et al*, 2012), and cycling stability (Espinosa-Angeles *et al*, 2021), are critical determinants of battery performance.

Specific capacity denotes the amount of charge that can be stored per unit mass or volume of the electrode material, reflecting its energy storage capacity.

Voltage refers to the electrochemical potential difference between the charged and discharged states of the electrode material, influencing the operating voltage range and energy output of the battery. Cycling stability pertains to the ability of the electrode material to maintain its electrochemical performance over repeated charge and discharge cycles, with minimal capacity fade and degradation.

3.2 Mechanical Properties

Mechanical properties, such as strength, flexibility, and structural stability, are essential considerations for electrode materials, particularly in flexible and portable battery applications (Xia *et al*, 2022). Electrode materials must withstand mechanical stresses and deformations during battery assembly, operation, and handling without compromising their structural integrity or electrical conductivity (Xu *et al*, 2020). Moreover, mechanical properties play a crucial role in preventing electrode delamination, cracking, and mechanical failure, which can lead to performance degradation and safety hazards (Naik *et al*, 2023), (Ling *et al*, 2015).

3.3 Thermal Stability

Thermal stability is paramount for electrode materials to withstand elevated temperatures encountered during battery operation and prevent thermal runaway events. Electrode materials should exhibit high thermal stability and resistance to thermal decomposition, ensuring safe and reliable battery performance under diverse operating conditions (Asakura *et al*, 2021). Thermal stability is particularly critical in high-power and fast-charging applications where heat generation and dissipation rates are elevated (Thakur *et al*, 2022). Additionally, thermal stability influences battery safety (Ge *et al*, 2020), longevity (Zhang, *et al*, 2021), and compatibility with thermal management systems (Lin *et al*, 2021).

5. Impact of Electrode Materials on Battery Performance

5.1 Lithium-Ion Batteries (LIBs)

In lithium-ion batteries (LIBs), electrode materials play a critical role in determining energy density, power density, and cycle life (Pender *et al*, 2020). The choice of electrode materials influences key performance metrics such as specific capacity, rate capability, and life span. Commonly used electrode materials for LIBs include lithium cobalt oxide (LCO) (Tang *et al*, 2018), lithium nickel manganese cobalt oxide (NMC) (Deng *et al*, 2010), and lithium iron phosphate (LFP) (Li *et al*, 2021).

5.2 Sodium-Ion Batteries (SIBs)

Sodium-ion batteries (SIBs) have emerged as promising alternatives to LIBs due to the abundance and low cost of sodium resources (Xiong *et al*, 2011). Electrode materials for SIBs exhibit similar electrochemical properties to their lithium counterparts but must accommodate the larger ionic radius of sodium ions (Wasalathilake *et al*, 2020). Commonly investigated electrode materials for SIBs include sodium transition metal oxides (e.g., sodium cobalt oxide, sodium manganese oxide) (Shen *et al*, 2021) and carbon-based materials (Zhang *et al*, 2022).

5.3 Beyond Lithium-Ion Batteries

Beyond lithium-ion batteries encompass a diverse range of emerging battery chemistries, including magnesium-ion batteries (MIBs) (Zhang *et al*, 2022), (Regulacio *et al*, 2021), potassium-ion batteries (PIBs) (Hassoun & Scrosati, 2015), and solid-state batteries (Hassoun & Scrosati, 2015).

MIBs utilize magnesium-based electrode materials such as magnesium alloys, magnesium oxides, and magnesium-intercalation compounds. PIBs employ potassium-intercalation electrode materials such as potassium transition metal oxides and Prussian blue analogs.

Solid-state batteries utilize solid electrolytes and electrode materials such as sulfides, oxides, and polymer composites to enable safer, higher-energy-density battery designs. Research efforts in BLIBs are focused on overcoming challenges related to electrode materials' ion diffusion kinetics, volumetric expansion, and interface stability to realize their full potential for next-generation energy storage applications (Hassoun & Scrosati, 2015).

6. Motivation for Activated Charcoal as an Electrode Material

In recent years, there has been growing interest in exploring alternative electrode materials with the aim of enhancing battery performance while mitigating environmental impact.

Activated charcoal, derived from various renewable sources such as biomass, agricultural waste, and recycled materials, has emerged as a promising candidate for sustainable electrode materials in batteries (Benítez *et al*, 2021), (Hernández-Rentero *et al*, 2020).
Activated or nanoporous carbon characterized by its high surface area, porous structure, chemical stability, and low cost, making it an attractive option for energy storage applications is a key material for the electrodes of commercial supercapacitors available at this time (Jänes *et al*, 2007).
The cell electrode has a porous structure at nanoscale level and this provides high value of capacitance than in the case of traditional electrolytic capacitors (Zhang & Tang, 2020).
Values of the electric capacitance reaching thousands of Farads are possible at reasonable size of the cell, due to large specific exposed area of the electric double layer formed at the nanoporous carbon – electrolyte interface (Burt *et al*, 2016).
Different precursors such as coke, coal, wood, fruit and coffee remains or starch have been used and investigated to obtain activated carbon, for higher performance electrodes (Iwanow *et al*, 2020), (Elmouwahidi, *et al*,2012), (Hamouda *et al*, 2020).
Moreover, an optimum material achieving high performance and low cost is still a matter of research and development with improvement in the properties of commercial activated carbon is required for higher supercapacitor performance.

Table 1. Physical properties of activated charcoal (Jänes *et al*, 2007)

Property	Magnitude
Solid density (g/cm3)	0.48
Pore volume (ml/g)	0.73
Packing density (g/cm3)	0.53
Surface area (m2/g)	900-1100
Particle size (mm)	0.50-2.36

7. Advantages of Activated charcoal over conventional electrode materials

7.1 Abundant and Renewable Resource

One of the primary motivations for employing activated charcoal as an electrode material is its abundance and renewability. Activated charcoal is derived from natural carbonaceous sources, such as coal, wood, coconut shells, and agricultural residues. These raw materials are widely available and can be sustainably sourced, making activated charcoal an environmentally friendly option for electrode fabrication. Moreover, advancements in biomass conversion technologies have enabled the production of activated charcoal from waste biomass, further enhancing its sustainability profile.

7.2 High Surface Area and Porosity

Activated charcoal exhibits an exceptionally high surface area and porosity, making it an ideal candidate for electrode materials in energy storage devices. During the activation process, the precursor material is subjected to high temperatures and chemical treatments, resulting in the formation of a network of micropores and mesopores throughout the charcoal structure. This increased surface area and porosity provide abundant active sites for electrochemical reactions, facilitating rapid ion transport and enhancing electrode performance.

7.3 Tailorable Pore Structure

Another key advantage of activated charcoal is its tailorable pore structure, which can be customized to suit specific application requirements. By adjusting the activation parameters such as temperature, duration, and activation agent concentration, researchers can control the size, distribution, and surface chemistry of pores in activated charcoal. This tunability enables optimization of ion diffusion kinetics, electrolyte accessibility, and electrochemical stability, thereby enhancing the overall efficiency and performance of energy storage devices.

7.4 Superior Electrochemical Properties

Activated charcoal exhibits favorable electrochemical properties, including high electrical conductivity, low resistance, and excellent chemical stability, making it well-suited for electrochemical applications. Its intrinsic conductivity allows for efficient electron transport within the electrode matrix, minimizing internal losses and improving energy conversion efficiency. Additionally, activated charcoal is chemically inert and resistant to corrosion, ensuring long-term stability and reliability in harsh operating environments.

7.5 Compatibility with Aqueous and Non-Aqueous Electrolytes

Activated charcoal demonstrates compatibility with a wide range of electrolytes, including aqueous and non-aqueous solutions, offering versatility in battery and supercapacitor applications. In aqueous systems, such as aqueous electrolyte capacitors and

aqueous sodium-ion batteries, activated charcoal electrodes exhibit high capacitance, fast charge-discharge kinetics, and excellent cycling stability. In non-aqueous systems, such as lithium-ion batteries and organic electrolyte capacitors, activated charcoal electrodes offer superior energy density, extended cycle life, and enhanced safety performance.

7.6 Low Cost and Scalability

Activated charcoal is a cost-effective electrode material compared to other carbon-based materials such as graphene and carbon nanotubes. Its low production cost, coupled with its abundance and renewability, makes activated charcoal an economically viable option for large-scale electrode fabrication. Moreover, the scalability of activated charcoal production processes, such as physical activation and chemical activation methods, enables mass production of electrodes to meet the growing demand for energy storage devices in various sectors.

7.7 Environmental Sustainability

Utilizing activated charcoal as an electrode material aligns with the principles of environmental sustainability and green technology. By leveraging renewable biomass feedstocks and employing eco-friendly activation processes, the production of activated charcoal minimizes environmental impact and reduces carbon footprint. Additionally, the use of activated charcoal in energy storage devices contributes to the development of clean energy technologies and promotes the transition towards a low-carbon and sustainable energy future.

Given these favorable attributes, activated charcoal holds significant promise for addressing the dual challenges of sustainability and performance in battery technology.

However, realizing the full potential of activated charcoal as an electrode material requires advancements in material synthesis, electrode design, manufacturing processes, and performance optimization.

8. Activation of Charcoal

The activation of charcoal involves treating it with a gas or chemical to increase its surface area and make it more porous, which enhances its ability to adsorb substances. This process typically involves heating the charcoal to high temperatures in the presence of an activating agent, such as steam or chemicals like zinc chloride or phosphoric acid. The activation removes impurities and creates a network of pores, increasing the charcoal's adsorption capacity. Activated charcoal finds wide applications in various fields, including water purification, air filtration, gas masks, medical treatments, and industrial processes.
(Songlin & Morita, 2010)

Figure 5. Activation of charcoal (Kim *et al*, 2020))

8.1 Physical Activation Processes

Physical activation methods involve the carbonization of biomass precursor materials followed by the activation of the resulting carbonized char using gases such as carbon dioxide or steam (Teng & Wang, 2000). The activation temperature, duration, and choice of precursor materials significantly influence the properties of the activated charcoal and, consequently, the performance of the electrodes. Higher activation temperatures generally result in increased surface area and porosity, leading to improved electrode performance (Kim *et al*, 2020). However, optimizing activation parameters to achieve the desired balance between porosity, surface area, and mechanical strength is crucial for scalability.

Scalability considerations for physical activation processes primarily revolve around the efficiency and throughput of the activation equipment. Traditional batch-based activation methods may be limited in scalability due to long processing times and equipment constraints. Continuous or semi-continuous activation processes, such as rotary kilns or fluidized bed reactors, offer higher throughput and scalability but require careful control of process parameters to ensure consistent product quality (Dhamodaran & Babu, 2011).

Challenges associated with physical activation techniques include the uniformity of activation across large batches, control of pore size distribution, and potential equipment maintenance issues (Yi *et al*, 2021).

Addressing these challenges through process optimization, automation, and innovative reactor designs is essential for scaling up the production of activated charcoal-based electrodes.

8.2 Chemical Activation Processes

Chemical activation methods involve impregnating the carbonized precursor materials with activation agents such as ($ZnCl_2$, KOH, NaOH, H_3PO_4, K_2CO_3, and $FeCl_3$) potassium hydroxide (KOH) or phosphoric acid (H_3PO_4) followed by thermal treatment (Heidarinejad *et al*, 2020). Chemical activation typically results in higher surface area and pore volume compared to physical activation methods, leading to superior electrochemical performance (Wei *et al*, 2019). However, scalability considerations for chemical activation processes differ from those of physical activation due to the additional steps involved in the activation process.
Comparison of chemical activation with physical activation in terms of scalability and electrode performance requires careful evaluation of the trade-offs between process complexity, cost, and product quality.
While chemical activation may offer higher surface area and pore volume, it often requires more stringent process control and waste management measures, which can impact scalability and environmental sustainability.
Optimization strategies for enhancing electrode properties during chemical activation include controlling the concentration and type of activation agent, optimizing impregnation and activation conditions, and post-treatment processes to remove residual impurities. Balancing these factors to achieve the desired electrode performance while maintaining scalability is essential for the commercialization of activated charcoal-based electrodes.

9. Scalable Manufacturing Techniques for Activated Charcoal-Based Electrodes

The widespread adoption of activated charcoal-based electrodes in energy storage applications necessitates scalable manufacturing techniques to meet the growing demand for sustainable battery solutions (Lee *et al*, 2019).
Electrode assembly involves the integration of activated charcoal-based electrodes into commercial battery cell configurations, typically in combination with separator and electrolyte materials. Electrode manufacturing processes such as slurry coating, calendaring, and drying are employed to produce uniform and defect-free electrodes with the desired thickness and porosity (Safari, 2022).
Scalability considerations for electrode assembly and manufacturing processes include optimizing coating and drying techniques to achieve high throughput and reproducibility while minimizing material waste and energy consumption (Bryntesen *et al*, 2021). Continuous or roll-to-roll manufacturing approaches offer scalability advantages over batch-based processes but require careful control of process parameters to maintain product quality (Rahimi *et al*, 2018).
Integration of activated charcoal-based electrodes into commercial battery cell configurations involves assembling electrodes into electrode stacks, followed by cell casing, electrolyte filling, and sealing (Wang *et al*, 2020).
Scalable assembly techniques such as automated assembly lines or robotic systems may be employed to streamline production and ensure consistency in battery performance and quality.
Considerations for scalability, uniformity, and reproducibility in electrode manufacturing require close collaboration between materials scientists, process engineers, and battery manufacturers to optimize production processes, minimize costs, and accelerate the commercialization of activated charcoal-based electrodes for various energy storage applications.

9.1 Slurry Preparation

Active Material (AM), binder (acting as a glue) and a conductive agent mixed together in specific mass ratios to make the composite electrode (CE). The effect of the mixing sequence on the morphology of the CE and the electrochemical performances was discussed by Chang et al (Li *et al*, 2009). They claim that the order of mixing should be optimized as a function of the constituents' properties, the nature of the solvent, and the viscosity of the dispersion. In order to compensate for the low AM conductivity, electron-conductive additives are generally employed to prepare CE for LIB. They can increase the available capacity, charge-discharge rate, and the cycle life performance of the cell. These electron-conductive additives are mainly conductive carbon particles, such as acetylene black, Ketjen black, super-P, carbon graphite, carbon nano-tubes etc.; however, these additives have a large surface area, which could lead to parasitic reactions with electrolytes (Hekmatfar *et al*, 2019).
The use of more fiber shaped carbons instead of more spherical Carbon Black (CB) enhances percolating properties of the electrode matrix (Payandehpeyman, & Mazaheri,2022). Positive Electrodes (PEs) consist of Lithium metal oxide mixed with CB and polyvinylidene difluoride (PVDF).
PVDF is dissolved in N-Methyl-2-pyrrolidone (NMP). Given its toxic nature, relative low vapor pressures and high boiling point, there is a great drive to ban NMP from the manufacturing process. For the Negative Electrodes (NE), it has been successfully replaced by using a carboxymethyl cellulose based binder in combination with styrene butadiene rubber. In this case, water can be used as a solvent. Today, in the majority of LIBs, carbon is used as AM for the NE (Wen *et al*, 2013). CB can also be added to the NE to improve conductive pathways and the porous structure. The conduction network is formed by the CB particles, which fill the void between AM particles and are interconnected by particle-to-particle point contacts from the current collector to the most outer AM

layer. The electronic transfer at the CB/CB contact points is due to the tunneling effect phenomenon. It was demonstrated that a good carbon coating with a homogeneous distribution can decrease the amount of CB to 2 wt % and also increase the kinetics of the resulting electrode when compared to a conventional electrode (Liu *et al* ,2010). It presents an opportunity for cell manufacturers to tune their cell performance. Especially for badly conducting AM, the influence of binders and conductive agents can be very influential (Li *et al*, 2020).

In addition, the solvent concentration is an important factor in the process and standard formulation of CEs. For a concentration below the optimal one, the electrode dispersion exhibits a yield stress that inhibits flow and prevents homogeneous distribution of the constituents. Above the optimal concentration, settling of the low viscosity dispersion can create a concentration gradient. Thus, the solvent concentration (or solid loading) has a strong impact on the morphology and consequently on the electrochemical performance of the CE. Below and above the optimal solvent concentration, the electrochemical behavior is degraded due to poor electronic wiring of the AM (Zhang & Cummings 2019).

9.2 Coating and Drying

Through a tape casting procedure, the electrode slurry (or paste) is applied onto the current collectors. Copper serves as the current collector for the negative electrode (NE), while aluminum serves this purpose for the positive electrode (PE). It is essential to manage the solvent concentration during this process. Once the powders are dispersed, the slurry is spread onto the current collector using a doctor blade to achieve a desired thickness. Drying the tape cast is necessary to remove residual solvents, ensuring a uniform coating thickness. The quantity of active material per square centimeter of current collector dictates the Maximum Available Capacity (MAC) of the electrodes. Balancing both electrodes is crucial to utilize the desired voltage window effectively. Additionally, irreversible capacity loss due to Solid Electrolyte Interphase (SEI) formation, primarily on the graphite-based NE, needs consideration. As the cell is assembled using unlithiated carbon and fully lithiated lithium metal oxide, representing a discharged state, the PE is not optimally utilized. Following coating, the electrodes undergo oven drying to remove the solvent: N-Methyl-2-pyrrolidone (NMP) for the PE and water for the NE (Mazouzi *et al*, 2014).

9.3 Calendering

During calendering, the electrodes are compressed by driving them through two massive cylindrical rolls. By applying large pressure (300–2000 $kg \cdot cm^{-2}$), the electrode thickness is reduced to a controlled value. The porosity is reduced around 40% (Karkar *et al*, 2017). As a result, the adhesion of electrode materials is improved and the density is increased. The effects on battery performance are discussed in the next paragraph. After this operation the electrodes can be dried for a second time to remove all water contamination. The rest of the manufacturing process will take place in a dry room.

9.4 Cutting/Slitter/Puncher

Then the electrodes are cut or punched into strips of a desired shape. A clean cut is necessary to avoid burrs on the edges which can cause short-circuit in the cells. Note that NEs are made slightly larger than PEs to avoid lithium deposition and dendride formation on the edge of the NE.
A large oversizing of the NE leads to a loss of energy density of the complete cell. Contacting tabs are fixed to the electrode (Zhao *et al*, 2015).

9.5 Assembly

The electrodes are wounded or stacked together with the separator. The electrode stack or jelly roll is integrated into the housing. To evacuate gases which arise during the formation, the housing is partially sealed (Bond *et al*, 2017).

9.6 Electrolyte Injection, Formation and Wetting

Finally, electrolytes are injected. To achieve a maximal wettability, it is important that the electrolyte completely permeates and fills the pores in the separator and electrode (Davoodabadi *et al*, 2020). Un-wetted AM area will decrease the specific surface area which is reacting during battery operation and as result increase the cell impedance. Furthermore, wettability is important to achieve a uniform SEI layer during the formation cycles. The calendering step will inevitably influence the wettability because it alters the porosity and particle distribution (Huttner *et al*, 2021).

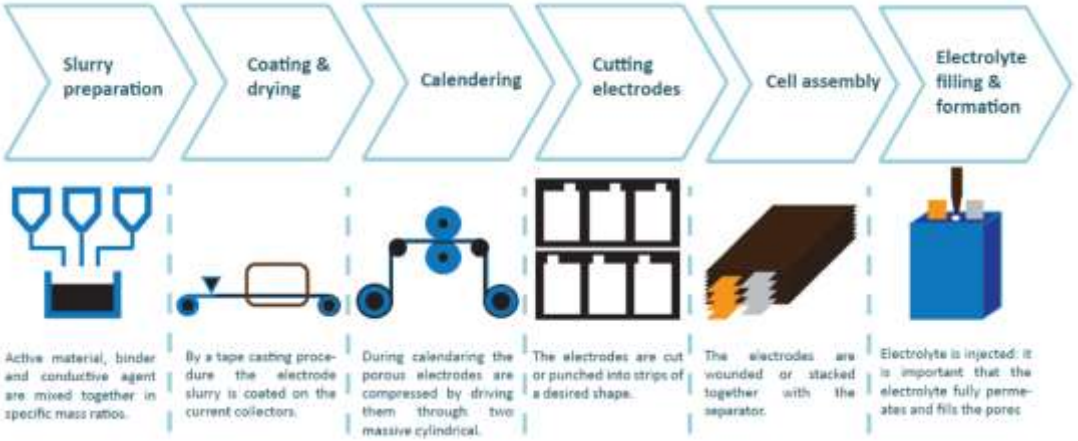

Figure 4. Electrode production process (Davoodabadi *et al*, 2020)

10. Influence of Manufacturing Parameters on Electrode Performance

Manufacturing parameters play a critical role in determining the performance, efficiency, and reliability of activated charcoal-based electrodes in energy storage devices. This section explores the influence of key manufacturing parameters, including porosity, surface area, morphology, and microstructure, on electrode performance.

10.1 Porosity and Surface Area Control

Porosity and surface area are fundamental characteristics of activated charcoal-based electrodes that significantly impact electrode kinetics, ion diffusion, and electrolyte accessibility. A higher porosity and surface area facilitate faster ion transport and increase the number of active sites available for electrochemical reactions, thereby enhancing battery performance (Haverkort, 2019).

Methods for controlling pore structure during electrode manufacturing include templating, chemical activation, and physical activation techniques (Tucker *et al*, 2015).

Optimizing porosity and surface area involves balancing the need for high electrochemical activity with mechanical stability and structural integrity. Fine-tuning activation parameters such as temperature, activation time, and activation agent concentration allow for precise control over pore structure and surface morphology, ultimately optimizing electrochemical performance.

10.2 Morphology and Microstructure Engineering

The morphology and microstructure of activated charcoal-based electrodes play a crucial role in active material utilization, charge transfer kinetics, and cycling stability. The arrangement of pores, particle size distribution, and surface morphology influence ion diffusion pathways, electrode-electrolyte interactions, and mechanical stability during cycling.

Engineering approaches to tailor electrode microstructure include particle size control, surface functionalization, and binder optimization (Moussaoui *et al*, 2020). By optimizing electrode morphology, it is possible to improve ion transport kinetics, minimize electrode polarization, and enhance cycling stability.

Advanced characterization techniques such as electron microscopy, X-ray diffraction, and spectroscopic analysis are employed to characterize electrode microstructure and elucidate its impact on electrochemical performance.

10.3 Scalability Challenges and Solutions

Key scalability challenges include process complexity, equipment limitations, and the need for consistent product quality across large production volumes.

Innovative solutions and process optimizations are required to overcome these challenges and enable the mass production of high-performance electrodes.

Innovative solutions for scalability include the development of continuous manufacturing processes, automation of production lines, and the implementation of advanced process control systems (Yang *et al*, 2023).

By streamlining production workflows, minimizing material waste, and optimizing resource utilization, it is possible to achieve cost-effective and sustainable electrode manufacturing at scale.

Case studies highlighting successful scalable electrode manufacturing processes in commercial battery applications demonstrate the feasibility and benefits of implementing innovative manufacturing techniques (Pfleging, 2020). These case studies showcase real-world examples of process optimization, technology transfer, and collaboration between industry stakeholders to accelerate the commercialization of activated charcoal-based electrodes for diverse energy storage applications.

11. Recent Advancements and Future Directions on battery technology

Recent advancements in electrode materials research have driven significant progress in battery technology, paving the way for safer, more efficient, and sustainable energy storage solutions. Emerging trends and future directions in electrode materials research encompass several key areas:

I. *Advanced Characterization Techniques*: Advancements in analytical and characterization techniques, such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), and spectroscopic analysis, enable in-depth characterization of electrode materials at the nano- and atomic scales, providing insights into their structure-property relationships and electrochemical behavior (Meng *et al*, 2017).
II. *Novel Synthesis Methods*: The development of novel synthesis methods, including templated growth, solvothermal synthesis, and electrodeposition techniques, offers new avenues for tailoring electrode materials' composition, morphology, and surface chemistry to achieve enhanced electrochemical performance and energy storage capabilities (Xu *et al* ,2016).
III. *Sustainable Materials Development*: The integration of sustainable materials and manufacturing practices into electrode materials research, such as utilizing renewable resources, green solvents, and eco-friendly processing techniques, contributes to reducing the environmental footprint of battery production and promoting a circular economy (Lu & Chen 2020).
IV. *Integration with Energy Storage Systems*: The integration of electrode materials with advanced energy storage systems, including hybrid energy storage systems, flow batteries, and integrated energy management platforms, presents opportunities for optimizing battery performance, enhancing grid stability, and enabling synergistic interactions between renewable energy sources and energy storage technologies (Fang *et al*, 2018).

12. Emerging Trends and Future Directions

Emerging trends in electrode material design, processing, and integration are shaping the future of sustainable battery technologies. Key areas of focus include:

I. **Advanced Electrode Materials:** Researchers are exploring novel electrode materials beyond traditional activated charcoal, including carbon nanomaterials, metal-organic frameworks (MOFs), and 2D materials. These materials offer unique properties such as high conductivity, large surface area, and tunable pore structures, enabling improved battery performance and energy density (Cruz-Navarro *et al*, 2020).
II. **Additive Manufacturing:** Additive manufacturing techniques, such as 3D printing, hold promise for the rapid prototyping and customization of electrode structures. By precisely controlling material deposition and geometry, additive manufacturing allows for the fabrication of complex electrode architectures with tailored properties, opening up new possibilities for electrode design and optimization (Browne *et al*, 2020).
III. **Innovative Manufacturing Processes:** Innovations in electrode manufacturing processes, such as roll-to-roll processing, laser patterning, and inkjet printing, are revolutionizing the production of scalable electrodes. These techniques offer high throughput, precision, and flexibility, allowing for the cost-effective production of electrodes with enhanced performance and reliability (Kang, *et al*, 2018).
IV. **Integration of Sustainable Materials:** The integration of sustainable materials and manufacturing practices is becoming increasingly important in the development of eco-friendly battery technologies. Researchers are exploring renewable carbon sources, green solvents, and environmentally friendly processing techniques to minimize the environmental footprint of battery production while maximizing energy efficiency and performance (Lee *et al*, 2017).

13. Potential Implications for Commercialization

The advancements in scalable manufacturing techniques for activated charcoal-based electrodes have significant implications for the commercialization and widespread adoption of sustainable battery technologies (Ko *et al*, 2016), (Xiong, *et al*, 2018).

These include:

1. ***Cost Reduction*:** Scalable manufacturing processes enable cost-effective production of electrodes, reducing manufacturing costs and making sustainable battery technologies more economically viable for mass adoption.
2. ***Performance Improvement*:** Advanced electrode materials and manufacturing techniques result in electrodes with enhanced performance, including higher energy density, faster charging rates, and longer cycle life, thereby improving the overall efficiency and reliability of battery systems.
3. ***Market Penetration*:** With improved performance and reduced costs, sustainable battery technologies are poised to penetrate diverse markets, including electric vehicles, renewable energy storage, consumer electronics, and grid-scale applications, driving the transition towards a low-carbon energy future.

4. ***Environmental Benefits*:** By utilizing renewable materials and eco-friendly manufacturing processes, sustainable battery technologies offer environmental benefits such as reduced carbon emissions, resource conservation, and waste minimization, contributing to a more sustainable and resilient energy infrastructure.

14. Conclusion

The review has highlighted the significance of scalable manufacturing techniques in overcoming key challenges linked with the production of activated charcoal-based electrodes for batteries. It has elucidated the influence of manufacturing parameters such as porosity, surface area, morphology, and microstructure on electrode performance, emphasizing the need for precise control and optimization of manufacturing processes to achieve desired electrode properties.

Similarly, it has underscored the importance of advanced materials, innovative processing techniques, and sustainable manufacturing practices in driving the development and commercialization of activated charcoal-based electrodes.

By leveraging scalable manufacturing techniques, researchers and industry stakeholders can accelerate the transition towards sustainable battery technologies with improved performance, reliability, and environmental sustainability.

Eventually, electrode materials play a pivotal role in battery production, exerting a profound influence on battery performance, energy density, and cycle life. Therefore, through meticulous design, synthesis, and characterization, these materials can be tailored to meet specific application requirements and drive innovation in energy storage technology. As research efforts continue to advance, electrode materials are poised to enable the development of safer, more efficient, and sustainable battery solutions, accelerating the transition towards a greener and more resilient energy future.

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