Biomass-derived carbon materials for energy storage applications

Aurora Gómez Martín

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PhD Thesis presented by

Aurora Gómez Martín

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Supervisors:
Julián Martínez Fernández
Joaquín Ramírez Rico

Department of Condensed Matter Physics
University of Seville

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"You look at science (or at least talk of it) as some sort of demoralizing invention of man, something apart from real life, and which must be cautiously guarded and kept separate from everyday existence. But science and everyday life cannot and should not be separated. Science, for me, gives a partial explanation for life."

———— **Rosalind Franklin**

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Abstract

Energy storage systems are an essential link in the implementation of renewable energies and in the development of electric vehicles, which are needed to reduce our dependence on fossil fuels and the emission of greenhouse gases. Various technologies have been proposed for energy storage based on different working principles, including lithium-ion batteries, emerging sodium-ion batteries and electric-double layer capacitors. Besides the quest for improving key aspects such as energy and power densities, current research efforts are devoted to foster the manufacturing of more environmentally friendly devices using sustainable materials. Carbon-based electrodes hold considerable promise in such terms due to their low cost, tailorable morphology and microstructure, and the possibility of processing them by direct carbonization of eco-friendly and naturally-available biomass resources.

The main goal of this thesis is to develop carbon materials from biomass resources and study their applications as electrode for lithium-ion batteries, sodium-ion batteries and electric-double layer capacitors. En route towards that goal, it also aims at expanding our understanding of the microstructural changes of biomass-derived carbons with varying processing conditions and their effect on the electrochemical performance for each of these technologies.

The first part of this work reports on the synthesis of graphitized carbon materials from biomass resources by means of an Fe catalyst, and the study of their electrochemical performance as anode materials for lithium-ion batteries (LIBs). Peak carbonization temperatures between 850 °C and 2000 ºC were covered to study the effect of crystallinity, surface and microstructural parameters on the anodic behavior, focusing on the first-cycle Coulombic efficiency, reversible specific capacity and rate performance. Reversible capacities of Fe-catalyzed biomass-derived carbons were compared to non-catalyzed hard carbon and soft carbons materials heated up to 2800 ºC. Moreover, *in-situ* characterization experiments were carried out to advance our understanding of the mechanisms responsible for catalytic graphitization.

The second part of this work reports a comprehensive study on the structural evolution of hard carbons from biomass resources as a function of carbonization temperature (800 - 2000 ºC), and its correlation with electrochemical properties as anode materials for sodium-ion batteries (SIBs). Synchrotron X-ray total scattering experiments were performed and the associated atomic pair distribution function (PDF) extracted from the data to access quantitative information on local atomic arrangement in these amorphous materials at the nanoscale, as well as its evolution with increasing processing temperature. Then, electrochemical properties and the storage mechanisms involved on Na ions insertion into hard carbon structures at each characteristic potential regions were elucidated and correlated with microstructural properties.

Finally, the third part of this work reports on the synthesis of nanostructured porous graphene-like materials from biomass resources using an explosion-assisted activation strategy by nitrate compounds and Ni as a graphitization catalyst. The thermal behavior during carbonization as well as the resulting microstructural and surface properties were evaluated at two different processing temperatures, 300 and 1000 ºC. Finally, their application as electrode materials for electric-double layer capacitors (EDLCs) and LIBs is investigated, with a view to their performance under high charge/discharge specific current densities experiments.

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List of Abbreviations

AC	Activated Carbon
ASA	Active Surface Area
ATR	Attenuated Total Teflection
BET	Brunauer, Emmett And Teller
BJH	Barrett-Joyner-Halenda
BMD	Bockris-Müller-Devanathan
CE	Counter Electrode
CMC	Carboxymethyl Cellulose
CNT	Carbon Nanotube
CV	Cyclic Voltammetry
CVD	Chemical Vapour Deposition
DEC	Diethyl Carbonate
DF	Dark Field
DFT	Density Functional Theory
DGM	Dyglime
DMC	Dimethyl Carbonate
DSC	Differential Scanning Calorimetry
DTG	Differential Thermogravimetric
EC	Ethylene Carbonate
EDLC	Electric Double-Layer capacitor
EDX	Energy Dispersive X-Ray
EG	Expanded Graphite
EMC	Ethyl Methyl Carbonate
EV	Electric Vehicle
FEC	Fluoroethylene Carbonate
FTIR	Fourier Transform Infrared Spectroscopy
FWHM	Full Width at Half Maximum
GCD	Galvanostatic Charge/Discharge
GIC	Graphitic Intercalation Compunds
HAADF	High-Angle Annular Dark Field
HR	High-Resolution
HTT	Heat Treatment Temperature
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
IR	Infrared Radiation

LIB	Lithium Ion Battery
LTO	Lithium Titanate Oxide
MDF	Medium Density Fiberboard Wood
MNLDFT	Modified Non-Local Density Functional
NG	Natural Graphite
NMP	1-Methyl-2-Pyrrolidinone
OCV	Open-Circuit Potential
PC	Propylene Carbonate
PDF	Pair Distribution Function
PG	Pristine Graphite
PSD	Pore Size Distribution
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene Difluoride
RE	Reference Electrode
SA	Sodium Alginate
SAED	Selected Area Diffraction
SEI	Solid Electrolyte Interphase
SEM	Scanning Electron Microscopy
SG	Synthetic Graphite
SHE	Standard Hydrogen Electrode
SIB	Sodium Ion Battery
STEM	Scanning Transmission Electron Microscopy
TEM	Transmission Electron Microscopy
TGA	Thermogravimetric Analysis
TMO	Transition Metal Oxides
VC	Vinylene Carbonate
WE	Working Electrode
XPS	X-Ray Photoelectron Spectroscopy
XRD	X-Ray Diffraction

Notation

α	Degree of graphitization
β	Concentration of defects
at.	Atomic
CE	Coulombic efficiency
d_{002}	Interplanar distance
dQ/dV	Differential capacity plot
I_c	Charge current
I_d	Discharge current
I_{D1}/I_G	Raman intensity ratio between D_1 and G bands
L_a	Crystallite size along the basal plane of graphite
L_c	Crystallite size along the stacking direction of graphite
MDF Fe	Medium density fibreboard-derived carbon treated with Fe
MDF Ni H$_2$O	Medium density fibreboard-derived carbon treated with water-based nickel nitrate solution
MDF Ni isop	Medium density fibreboard-derived carbon treated with isopropanol-based nickel nitrate solution
P/P_0	Relative pressure
P_0	Saturation pressure
Q	Capacity
Q_{ch}	Charge capacity
Q_{dis}	Discharge Capacity
Q_{irr}	Irreversible capacity
Q_{rev}	Reversible capacity
t_c	Charge time
t_d	Discharge time
v/v	Volume to Volume Ratio
wt.	Weight

Chapter 1
Introduction

Contents

1.1. Motivation

As a result of climate change and global economic growth, the topic of energy supply and storage has emerged as one of the main issues that humanity faces and, despite their impact in global warming, fossil fuels still remain our main source of energy (*1*). However, due to the global concerns regarding a future shortage of fossil fuels and raising levels of environmental pollution, there is an urgent need to develop new renewable and sustainable energy sources.

Renewable energy sources, such as solar or wind, have been steadily increasing in recent years (*2*), but still fall short on supplying energy in a stable and continuous manner due to their strong dependence on atmospheric conditions, which means that peak renewable production normally occurs during periods of low energy demand. Thus, one of the current topics of study is the implementation of large-scale energy storage systems next to power plants to offset the problem of continuity of supply and endow such technologies with future prospects (*3*). In addition, the growing market of electric vehicles with lower CO_2 emissions and portable electronic devices has also prompted the development of energy storage technologies (*4, 5*).

The development and improvement of energy storage systems constitutes one of the greatest challenges of present times and has become a primary focus in the scientific and industrial communities (*6*). Among the variety of systems based on either chemical or physical processes that are capable of storing electrical energy, two major technologies are nowadays in the front line: rechargeable batteries and supercapacitors (*7*). Lithium-ion rechargeable batteries represent the state-of-the-art technology for portable and electric vehicles applications due to their high gravimetric and volumetric energy densities, despite their poor power density (*8*). Alternatively, sodium-ion batteries have been proposed as alternative devices to lithium-ion batteries because of the wider availability of source materials and lower manufacturing costs. Meanwhile, supercapacitors deliver excellent cyclic stability and power density, but have rather low energy densities.

Besides the quest for higher energy and power densities, there is interest in developing more environmentally-friendly processes for the manufacturing of these devices, as currently state-of-the-art systems rely on scarce resources, the extraction of which has a tremendous environmental impact (*9,*

10). Despite intensive effort devoted to find alternative active materials for electrode formulation, carbon materials are still at the forefront of research due to their interesting intrinsic physicochemical properties such as good electrical conductivity, high chemical stability, tailorable surface properties and ease of processing. Carbon materials can be easily obtained from carbonization of naturally available biomass resources, making their synthesis eco-friendly and cost-effective in a circular economy framework (*11*). However, further efforts are needed to optimize the electrochemical performance of biomass-derived carbon electrodes. Our understanding of how the carbon microstructure and surface properties evolve with processing conditions and their effect on the electrochemical properties is still lacking.

1.2. Aim and objectives of the thesis

The main goal of this thesis is to develop sustainable carbon materials from biomass resources, for their use as electrodes in energy storage systems such as lithium-ion batteries, sodium-ion batteries and supercapacitors. To achieve this goal, we need to establish a correlation between electrochemical properties and structural aspects of the materials, and understand how they are influenced by processing conditions. Accordingly, the specific objectives addressed along the thesis are as follows:

- Explore routes to obtain highly crystalline graphitic materials from biomass resources, by using Fe as a catalyst to induce graphitization at low temperatures (850 - 2000 ºC), as well as to contribute to our understanding of the mechanisms responsible for catalytic graphitization.
- Evaluate the electrochemical properties of Fe-graphitized carbons as anodes for lithium-ion batteries and investigate the influence of processing, microstructural and surface parameters on the anodic electrochemical properties.
- Study the effect of processing parameters on the microstructural and textural characteristics of biomass-derived hard carbon materials (800 - 2000 ºC). Carry out a comprehensive study on their structural evolution and local range atomic order as a function of target processing temperature by alternative approaches.
- Evaluate the electrochemical properties of hard carbons from biomass resources as anodes for sodium-ion batteries. Obtain further insight into the storage mechanisms involved at characteristic potential regions and study the dependence of the structural evolution and microstructural features on the anodic electrochemical properties.
- Synthesis and microstructural characterization of nanostructured porous graphene-like carbon materials derived from biomass resources, using an explosion-assisted activation strategy by nitrate compounds and Ni as graphitization catalyst. Evaluation of their electrochemical properties as electrodes in supercapacitors as well as lithium-ion batteries.

1.3. Outline of the thesis

This thesis is structured in six chapters. This first chapter states the goals of this thesis, followed by an outline of each of the following chapters.

The second chapter reviews the classification of carbon materials in terms of their microstructure and the phenomena of catalytic graphitization process by transition metals. Then, the chapter gives an overview of current energy framework, energy storage devices technologies, and state-of-the-art carbonaceous electrode materials for lithium-ion batteries, sodium-ion batteries and electric double-layer capacitors.

The third chapter presents the main results of the graphitization of biomass resources by using Fe as a catalyst and the related microstructural and surface characterization as a function of treatment temperature. Then, the chapter focuses on the electrochemical study of these materials as anodes for lithium-ion batteries to discuss the correlation between microstructural features and anodic electrochemical properties.

The fourth chapter reports on the synthesis of hard carbons from biomass resources and their application as anode materials for sodium-ion batteries, in order to understand the relationship between microstructure and anodic electrochemical properties. This chapter gives significant insights into the sodium storage mechanisms at each characteristic potential regions, contributing to the current debate regarding storage mechanisms of sodium ions into hard carbon structures.

The fifth chapter presents the results of the thermal and microstructural characterization of porous graphene-like carbon materials synthetized by an explosion-assisted activation strategy using highly concentrated nickel nitrate solution as the activating agent. Then, the electrochemical performance of these materials as electrodes for supercapacitors and lithium-ion batteries is reported.

Third, fourth and fifth chapters include each a brief scientific background of previous works on specific topics to better understand the main motivation of performing such investigations.

Finally, the sixth chapter outlines the main contributions of this thesis to each of the topics covered and the main conclusions. In addition, some possible future research lines are presented.

1.4. List of publications

The following works are original and fully carried-out by the author and co-authors during the thesis period. The author has express authorization for using their content as parts of the thesis.

Papers in indexed journals directly related to this thesis:

1. **A. Gómez-Martín**, J. Martínez-Fernández, M. Ruttert, M. Winter, T. Placke and J. Ramírez-Rico.

"*New insights into the correlation of structure and performance of hard carbons as anodes for sodium ion batteries*" (under review).

2. **A. Gómez-Martín**, J. Martínez-Fernández and J. Ramírez-Rico. "*Porous graphene-like carbon from fast catalytic decomposition of biomass*" (under review).

3. **A. Gómez-Martín**, J. Martínez-Fernández, M. Ruttert, A. Heckhmann, M. Winter, T. Placke and J. Ramírez-Rico. "*Fe-catalyzed graphitized carbons from biomass resources as anode materials for lithium-ion batteries*". Chemsuschem *11, 2776 – 2787 (2018).*

4. **A. Gómez-Martín**, R. Chacartegui, J. Ramírez-Rico and J. Martínez-Fernández. "*Performance improvement in olive stone's combustion from a previous carbonization transformation*". Fuel *228, 254–262 (2018).*

Contributions to national and international conferences directly related to this thesis:

1. **A. Gómez-Martín**, J. Martínez-Fernández, M. Ruttert, T. Placke, M. Winter and J. Ramírez-Rico. "*New insights into the correlation of microstructure and electrochemical performance of hard carbons for sodium-ion batteries*". E-MRS 2019 Spring Meeting. Oral presentation. Nice (France). May, 2019.

2. **A. Gómez-Martín**, J. Martínez-Fernández, M. Ruttert, T. Placke and J. Ramírez-Rico. "*Hard carbon derived from olive stone as anode for sodium-ion batteries: Further insights into the microstructure on Na+ storage mechanisms*". 43rd International Conference & Exposition on Advanced Ceramics and Composites. Invited oral presentation. Daytona Beach (Florida). January, 2019.

3. A. Gómez-Martín, J. Martínez-Fernández and **J. Ramírez-Rico**. "*Porous graphene-like nanosheets from biomass resources as electrodes for energy storage applications*". 43rd International Conference & Exposition on Advanced Ceramics and Composites. Oral presentation. Daytona Beach (Florida). January, 2019.

4. **A. Gómez-Martín**, J. Martínez-Fernández and J. Ramírez-Rico. "*Nanostructured carbon materials from biomass resources as electrode for energy storage applications*". Multifunctional Materials (MultiMat) 2018 National Conference. Oral presentation. Granada (Spain). September, 2018.

5. **A. Gómez-Martín**, M. Ruttert, T. Placke, J. Martínez-Fernández and J. Ramírez-Rico. "*Fe-catalyzed graphitized carbons from biomass resources as anode materials for lithium-ion batteries*". Worldwide Carbon 2018 Conference. Oral presentation. Madrid (Spain). July, 2018.

6. **J. Ramirez-Rico**, A. Gómez Martín, J. M. Fernandez, M. Ruttert and T. Placke. "*Graphitized carbon materials from biomass resources as electrodes for energy storage systems*". 42nd International Conference & Exposition on Advanced Ceramics and Composites. Oral presentation. Daytona Beach (Florida). January, 2018.

7. **A. Gutiérrez-Pardo**, A. Gómez-Martín, J. Martínez-Fernández and J. Ramírez-Rico. "*Graphitization of cellulosic materials by means of an iron catalyst*". E-MRS 2016 Fall Meeting. Oral presentation. Warsaw (Poland). September, 2016.

Papers in indexed journals not directly related to this thesis:

1. **A. Gómez-Martín**, A. Gutiérrez-Pardo, J. Martínez-Fernández and J. Ramírez-Rico. "*Purification of wood-derived monolithic graphitized carbons for binder-free supercapacitor electrodes*". Submitted to Journal of Alloys and Compounds.

2. M. P. Orihuela, **A. Gómez-Martín**, J. A. Becerra, J. Serrano-Reyes, F. Jiménez-Espadafor and R.Chacartegui. "*Preliminary study on the performance of biomorphic Silicon Carbide as substrate for Diesel Particulate Filters*". Thermal Science **22** (5), 2053-2064 (2018).

3. M. P. Orihuela, **A. Gómez-Martín**, P. Miceli, J. A. Becerra, R. Chacartegui and D. Fino. "*Experimental measurement of the filtration efficiency and pressure drop of wall-flow Diesel Particulate Filters (DPF) made of biomorphic Silicon Carbide using laboratory generated particles*". Applied Thermal Engineering **131**, 41-53 (2017).

4. M. P. Orihuela, **A. Gómez-Martín**, J. A. Becerra, R. Chacartegui and J. Ramírez-Rico. "*Performance of biomorphic silicon carbide as particulate filter in diesel boilers*". Journal of Environmental Management **203 3,** 907-919 (2017).

5. **A. Gómez-Martín**, M. P. Orihuela, J. Ramírez-Rico, R. Chacartegui and J. Martínez-Fernández. "*Thermal conductivity of porous biomorphic SiC derived from wood precursors*". Ceramics International **42**, 16220-16229 (2016).

6. **A. Gómez-Martín**, M. P. Orihuela, J. A. Becerra, J. Martínez-Fernández and J. Ramírez-Rico. "*Permeability and mechanical integrity of porous biomorphic SiC ceramics for application as hot-gas filters*". Materials and Design **107**, 450-460 (2016).

7. M. J. López-Robledo, **A. Gómez-Martín**, J. Ramírez-Rico and J. Martínez-Fernández, "*Sliding wear resistance of porous biomorphic SiC ceramics*". International Journal of Refractory Metals and Hard Materials **59**, 26-31 (2016).

Contributions to national and international conferences not directly related to this thesis:

1. **J. A. Becerra**, A. Castillo, H. Cifuentes, A. Gómez-Martín and R. Chacartegui. "*Densification of olive pit in pellet form*". 26th European Biomass Conference & Exhibition (EUBCE 2018). Poster presentation. Copenhague (Denmark). May, 2018.

2. **J. Ramirez-Rico**, J. M. Fernandez, A. Gomez Martin, P. Orihuela Espina, R. C. Martin and J. Becerra-Villanueva. "*Ceria-based catalytic regeneration of wall-flow Diesel Particulate Filters made of biomorphic Silicon Carbide*". 42nd International Conference & Exposition on Advanced Ceramics and Composites. Oral presentation. Daytona Beach (Florida). January, 2018.

3. P. Orihuela Espina, A. Gomez Martin, J. Ramirez-Rico, **J. M. Fernandez**, R. Chacartegui-Ramirez

and M. Singh. "*Bioceramic Substrates for Engineering Applications: Particles Filtration in Diesel Engines*". 42nd International Conference & Exposition on Advanced Ceramics and Composites. Oral presentation. Daytona Beach (Florida). January, 2018.

4. **M.P. Orihuela**, A. Gómez-Martín, J.A. Becerra-Villanueva, J. Serrano-Reyes, F. Jiménez-Espadafor and R. Chacartegui. "*Performance of biomorphic Silicon Carbide as substrate for DPF in an automotive diesel engine*". 12th Conference on Sustainable Development of Energy, Water, and Environment Systems (SDEWES 2017). Oral presentation. Dubrovnik (Croatia). October, 2017

5. **A. Gómez-Martín**, M.P. Orihuela, J. Martínez-Fernández, J. A. Becerra, R. Chacartegui and J. Ramírez-Rico. "*Assessment of the suitability of biomorphic silicon carbide for filtering applications at high temperatures*". LV National Congress of the Spanish Society of Ceramics and Glass (SECV). Invited oral presentation. Sevilla (Spain). October, 2016.

6. **M.P. Orihuela**, A. Gómez-Martín, J. A. Becerra Villanueva, J. Ramírez-Rico and J. Martínez-Fernández. "*Performance of biomorphic SiC as particulate filter in diesel engines*". LV National Congress of the Spanish Society of Ceramics and Glass (SECV). Oral presentation. Sevilla (Spain). October, 2016.

7. **M.P. Orihuela**, A. Gómez-Martín, J.A. Becerra, R. Chacartegui-Ramirez and J. Ramírez-Rico. "*Performance of biomorphic silicon carbide as particulate filter in a diesel boiler*". 11th Conference of Sustainable Development of Energy, Water and Environment systems (SDEWES 2016). Oral presentation. Lisbon (Portugal). September, 2016.

8. **A. Gómez-Martín**, M.P. Orihuela, J. Martínez-Fernández, J. A. Becerra, R. Chacartegui and J. Ramírez-Rico. "*Thermal conductivity and permeability simulations based on X-ray tomography of porous biomorphic SiC*". E-MRS 2016 Fall Meeting. Poster presentation. Warsaw (Poland), September, 2016.

9. **M.P. Orihuela**, A. Gómez-Martín, J. Ramírez-Rico, J. Martínez-Fernández and R. Chacartegui-Ramirez. "*Assessment of the suitability of bioSiC as substrate of DPFs*". Junior EUROMAT 2016. Lausanne (Switzerland). Oral presentation. July, 2016.

10. **A. Gómez-Martín**, M.P. Orihuela, J. Martínez-Fernández, J. A. Becerra, R. Chacartegui, J.Ramírez-Rico. "*Assessment of the suitability of biomorphic silicon carbide for filtering applications at high temperatures*". V Conference of Young Researchers of the Institute of Ceramics and Glass (ICV). Oral presentation. Madrid (Spain). July, 2016.

Awards in national and international conferences:

1. Award for best 2nd oral presentation: **A. Gómez-Martín**, M. Ruttert, T. Placke, J. Martínez-Fernández and J. Ramírez-Rico. "*Fe-catalyzed graphitized carbons from biomass resources as anode materials for lithium-ion batteries*". Worldwide Carbon 2018 Conference. Madrid (Spain). July, 2018.

2. Award for best 2nd oral presentation: **A. Gómez-Martín**, M.P. Orihuela, J. Martínez-Fernández, J. A. Becerra, R. Chacartegui, J.Ramírez-Rico. "*Assessment of the suitability of biomorphic silicon carbide for filtering applications at high temperatures*". V Conference of Young Researchers of the Institute of Ceramics and Glass (ICV). Madrid (Spain). July 5th, 2016.

1.5. References

1.   I. Dincer, C. Zamfirescu, in *Advanced Power Generation Systems*. (Elsevier, Boston, 2014), pp. 95-141.

2.   https://yearbook.enerdata.net/renewables/wind-solar-share-electricity-production.html.

3.   C. Zhang, Y.-L. Wei, P.-F. Cao, M.-C. Lin, Energy storage system: Current studies on batteries and power condition system. *Renewable and Sustainable Energy Reviews* **82**, 3091-3106 (2018).

4.   O. Gröger, H. A. Gasteiger, J.-P. Suchsland, Review—Electromobility: Batteries or Fuel Cells? *Journal of The Electrochemical Society* **162**, A2605-A2622 (2015).

5.   R. Schmuch, R. Wagner, G. Hörpel, T. Placke, M. Winter, Performance and cost of materials for lithium-based rechargeable automotive batteries. *Nature Energy* **3**, 267-278 (2018).

6.   A. S. Arico, P. Bruce, B. Scrosati, J.-M. Tarascon, W. van Schalkwijk, Nanostructured materials for advanced energy conversion and storage devices. *Nature Materials* **4**, 366-377 (2005).

7.   M. Winter, R. J. Brodd, What Are Batteries, Fuel Cells, and Supercapacitors? *Chemical Reviews* **104**, 4245-4270 (2004).

8.   T. Placke, R. Kloepsch, S. Dühnen, M. Winter, Lithium ion, lithium metal, and alternative rechargeable battery technologies: the odyssey for high energy density. *Journal of Solid State Electrochemistry* **21**, 1939-1964 (2017).

9.   D. Larcher, J. M. Tarascon, Towards greener and more sustainable batteries for electrical energy storage. *Nature Chemistry* **7**, 19-29 (2015).

10. B. Lee, Y. Ko, G. Kwon, S. Lee, K. Ku, J. Kim, K. Kang, Exploiting Biological Systems: Toward Eco-Friendly and High-Efficiency Rechargeable Batteries. *Joule* **2**, 61-75 (2018).

11. W. Long, B. Fang, A. Ignaszak, Z. Wu, Y.-J. Wang, D. Wilkinson, Biomass-derived nanostructured carbons and their composites as anode materials for lithium ion batteries. *Chemical Society Reviews* **46**, 7176-7190 (2017).