Development of Sustainable Electrochemical Supercapacitors from Food Waste

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Research Period: June - September 2023

With the demand for energy storage predicted to grow significantly, the limited supply of lithium for lithium-ion batteries presents a challenge that needs to be solved urgently by other forms of sustainable energy storage technology. Electrochemical double layer capacitors (EDLCs) offer a promising solution, with longer lifetimes and rapid charge/discharge capabilities. They suit intermittent renewable sources and remote energy supply. This study explores sustainable EDLCs using activated carbon derived from Maris Piper Potato peelings, a waste source rich in lignocellulosic content. The process involved physical activation with steam over chemical methods, aiming for eco-friendliness. The EDLCs' electrochemical performance was evaluated using Cyclic Voltammetry (CV) and Galvanostatic Charge/Discharge (GCD). While commercial AC outperformed potato peel-derived AC in specific capacitance and specific energy, their specific power was comparable and further refinement of the physical activation method could yield superior performance over commercially available activated carbon. The project's time-frame limited further exploration, but microwave-assisted physical activation holds promise for future work. This research introduces an innovative approach to sustainable energy storage using food waste, highlighting the potential for waste reduction and the possibility of an environmentally-friendly solution to the energy crisis at hand.

I. INTRODUCTION

The demand for sustainable energy storage technology has reached critical importance as we face the challenges of depleting resources and climate change. One such challenge lies in the finite supply of lithium, a crucial component in the production of lithium-ion batteries (Li-Ion). To put this into perspective, global energy storage capacity is projected to increase fifteen-fold between 2021 and 2030, with estimates reaching 1,194 GWh in 2030 compared to 56 GWh in 2021 [1]. Further, the International Renewable Energy Agency (IRENA) has stated that the share of non-fossil fuel-based generation sources, i.e., renewable energy sources should increase to 57% globally by 2030 to remain within the Paris Agreement's target of keeping the average global temperature rise below 2 °C [2]

In the pursuit of sustainable energy storage solutions, electrochemical double layer capacitors (EDLCs) emerge as a promising alternative. These EDLCs demonstrate significantly longer lifetimes, surpassing conventional batteries by an order of magnitude (e.g., 10^6 vs. 10^3 charge/discharge cycles). Furthermore, their remarkable ability to rapidly charge and discharge made them particularly suitable for harnessing energy from intermittent renewable sources like solar and wind, and they have been highly used in recent times for regenerative braking systems in electric vehicles. These renewable energy sources often generate substantial energy in short bursts, aligning perfectly with the fast-charging capabilities of EDLCs.[3] Additionally, the resilience of EDLCs enable their operation under harsh conditions, facilitating energy supply to remote areas that were previously disconnected from conventional grids, ultimately improving livelihoods for a more diverse range of people living in harsher conditions.[4]

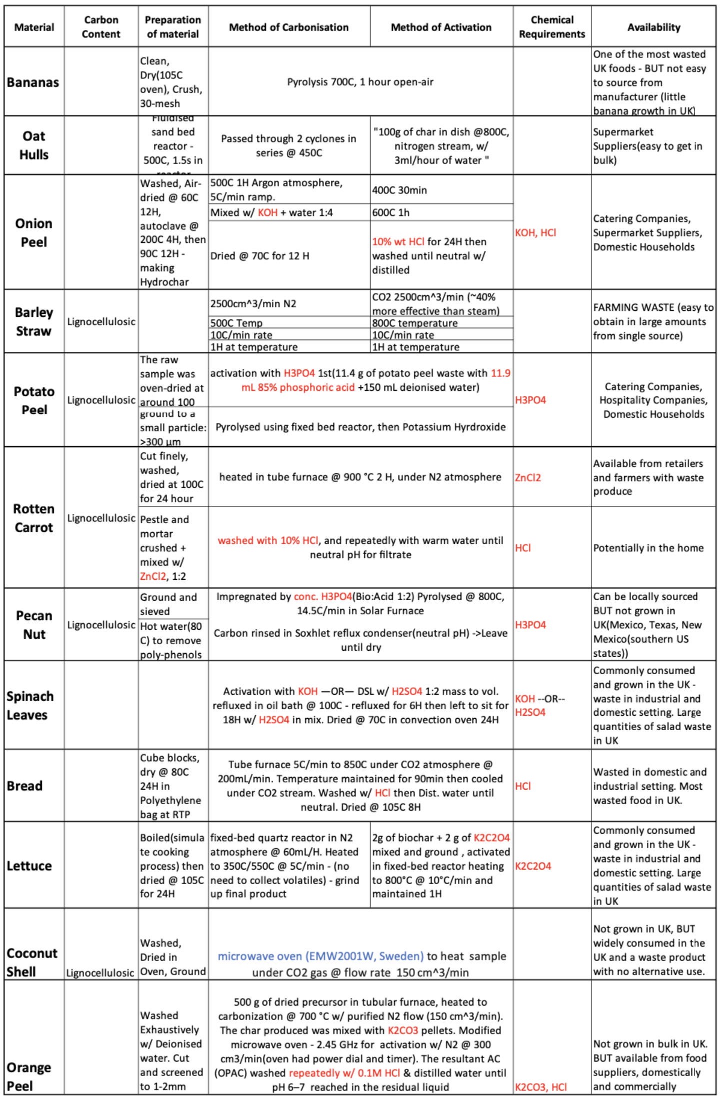
To create sustainable EDLCs, the research focused on utilizing activated carbon derived from biomass food waste sources to develop a sheet like material that could be cut into electrodes. Activated carbon is a form of carbon that has a sponge-like structure that allows electrolyte to penetrate the carbon structure. A UK government orchestrated inquiry found that 9.5 Mt (megatons) of food waste was generated in the UK across all the supply chain in 2018, leading to the greenhouse gas emissions of more than 25 Mt[5]. Thus using food waste as a primary component of EDLC electrode material, if the project were scaled industrially, would be an excellent food waste reduction strategy for reducing both the amount of wasted food destined for landfill and reducing the volume harmful greenhouse gases released, such as methane, in the decomposition process of food waste. Commonly wasted items of food in the UK were identified, and after a rigorous selection process(see literature review) Maris Piper Potato peelings were selected as the strongest candidate waste material to be converted into activated carbon to be ultimately used for creating activated carbon electrodes with a large pore size distribution with larger macropores($>$ 50nm) all the way down to the smallest micropores($<$ 2nm), referred to as hierarchical porosity.

II. LITERATURE REVIEW

The 3 key stages of the experiment were identifying suitable food waste materials, identifying a method of carbon activation and the creation of the EDLC test cell.
The selection process for suitable food waste materials involved firstly identifying the most wasted foods in the UK. By targeting domestically available waste sources, the research aimed to establish a scalable and sustainable approach that avoided the importation of food waste from overseas. This strategy not only minimized environmental burdens associated with transportation but also ensured a more self-sufficient and efficient waste management system. Promising candidate materials were identified through the literature based on their carbon content. Notably, lignocellulosic food wastes/biomass emerged as superior options due to their high carbon content and relatively lower ash content [8] meaning that a higher yield of activated carbon could be achieved through the activation process (See literature review matrix of candidate biomass waste materials at end of Literature Review section)

Potato peelings were identified as a strong candidate material due to their high lignin and cellulose content producing activated carbon with hierarchical porosity [6] whilst also being abundantly available in the UK, with the volume of harvested potatoes in the UK at 5.31 million metric tons[7]

To activate the carbon and maximize its electrochemical properties, the choice primarily favoured physical activation methods, where environmentally friendly reagents such as carbon dioxide and water were used at high temperatures, instead of chemical activation, where expensive and potentially toxic chemical reagents such as concentrated acids are utilised. Chemical activation can yield higher surface areas[9], which is desirable as a greater surface area is conducive to higher specific capacitances in EDLCs[10]. However, the environmental and sustainability implications associated with the use of concentrated chemicals such as hydrochloric acid and concentrated phosphoric acid necessitated a more eco-friendly approach to align with the project's motivations. Physical activation processes were selected to minimize potential hazards and reduce the environmental footprint.



Material	Carbon Content	Preparation of material	Method of Carbonisation	Method of Activation	Chemical Requirements	Availability
Bananas		Clean, Dry(105C oven), Crush, 30-mesh	Pyrolysis 700C, 1 hour open-air			One of the most wasted UK foods - BUT not easy to source from manufacturer (little banana growth in UK)
Oat Hulls		Fluidised sand bed reactor - 500C, 1.5s in reactor	Passed through 2 cyclones in series @ 450C	"100g of char in dish @800C, nitrogen stream, w/ 3ml/hour of water "		Supermarket Suppliers(easy to get in bulk)
Onion Peel		Washed, Air-dried @ 60C 12H, autoclave @ 200C 4H, then 90C 12H - making Hydrochar	500C 1H Argon atmosphere, 5C/min ramp. Mixed w/ KOH + water 1:4 Dried @ 70C for 12 H	400C 30min 600C 1h 10% wt HCl for 24H then washed until neutral w/ distilled	KOH, HCl	Catering Companies, Supermarket Suppliers, Domestic Households
Barley Straw	Lignocellulosic		2500cm^3/min N2 500C Temp 10C/min rate 1H at temperature	CO2 2500cm^3/min (~40% more effective than steam) 800C temperature 10C/min rate 1H at temperature		FARMING WASTE (easy to obtain in large amounts from single source)
Potato Peel	Lignocellulosic	The raw sample was oven-dried at around 100 ground to a small particle: >300 µm	activation with H3PO4 1st(11.4 g of potato peel waste with 11.9 mL 85% phosphoric acid +150 mL deionised water) Pyrolysed using fixed bed reactor, then Potassium Hyrdroxide		H3PO4	Catering Companies, Hospitality Companies, Domestic Households
Rotten Carrot	Lignocellulosic	Cut finely, washed, dried at 100C for 24 hour	heated in tube furnace @ 900 °C 2 H, under N2 atmosphere		ZnCl2	Available from retailers and farmers with waste produce
		Pestle and mortar crushed + mixed w/ ZnCl2, 1:2	washed with 10% HCl, and repeatedly with warm water until neutral pH for filtrate		HCl	Potentially in the home
Pecan Nut	Lignocellulosic	Ground and sieved Hot water(80 C) to remove poly-phenols	Impregnated by conc. H3PO4(Bio:Acid 1:2) Pyrolysed @ 800C, 14.5C/min in Solar Furnace Carbon rinsed in Soxhlet reflux condenser(neutral pH) ->Leave until dry		H3PO4	Can be locally sourced BUT not grown in UK(Mexico, Texas, New Mexico(southern US states))
Spinach Leaves			Activation with KOH —OR— DSL w/ H2SO4 1:2 mass to vol. refluxed in oil bath @ 100C - refluxed for 6H then left to sit for 18H w/ H2SO4 in mix. Dried @ 70C in convection oven 24H		KOH --OR-- H2SO4	Commonly consumed and grown in the UK - waste in industrial and domestic setting. Large quantities of salad waste in UK
Bread		Cube blocks, dry @ 80C 24H in Polyethylene bag at RTP	Tube furnace 5C/min to 850C under CO2 atmosphere @ 200mL/min. Temperature maintained for 90min then cooled under CO2 stream. Washed w/ HCl then Dist. water until neutral. Dried @ 105C 8H		HCl	Wasted in domestic and industrial setting. Most wasted food in UK.
Lettuce		Boiled(simulate cooking process) then dried @ 105C for 24H	fixed-bed quartz reactor in N2 atmosphere @ 60mL/H. Heated to 350C/550C @ 5C/min - (no need to collect volatiles) - grind up final product	2g of biochar + 2 g of K2C2O4 mixed and ground , activated in fixed-bed reactor heating to 800°C @ 10°C/min and maintained 1H	K2C2O4	Commonly consumed and grown in the UK - waste in industrial and domestic setting. Large quantities of salad waste in UK
Coconut Shell	Lignocellulosic	Washed, Dried in Oven, Ground	microwave oven (EMW2001W, Sweden) to heat sample under CO2 gas @ flow rate 150 cm^3/min			Not grown in UK, BUT widely consumed in the UK and a waste product with no alternative use.
Orange Peel		Washed Exhaustively w/ Deionised water. Cut and screened to 1-2mm	500 g of dried precursor in tubular furnace, heated to carbonization @ 700 °C w/ purified N2 flow (150 cm^3/min). The char produced was mixed with K2CO3 pellets. Modified microwave oven - 2.45 GHz for activation w/ N2 @ 300 cm3/min(oven had power dial and timer). The resultant AC (OPAC) washed repeatedly w/ 0.1M HCl & distilled water until pH 6–7 reached in the residual liquid		K2CO3, HCl	Not grown in bulk in UK. BUT available from food suppliers, domestically and commercially

FIG. 1: Table of biomass waste sources and the procedure followed in the literature to produce activated carbon from them. Note that where a chemical that is environmentally unfriendly has been used, it has been listed in red

III. METHODS

Establishing a method to follow throughout the whole experiment involved formulating a series of steps, based off common methods used in the literature to successfully activate carbon from Biomass waste sources by physical activation with steam. Physical activation using carbon dioxide gas rather than steam has, in some cases, yielded a greater surface area when activating some Biomass waste sources [11]. However given the environmental burden of ordering compressed CO_2 gas and releasing it into the atmosphere, steam was pursued in spite of the fact it would potentially yield an inferior product. However, steam was a reagent that had no environmental concerns surrounding it, with the only environmental burden being the energy required to heat the water bath, containing the bubbler, to 50^{o}C.

The Maris Piper potatoes were initially purchased from a local Tescos Supermarket, after which they were then stored in a dark cupboard for 3 weeks. At the point of peeling the potatoes they had slightly softened and were growing considerable numbers of shoots with some potatoes beginning to show mould on the surface. The potato peel was washed thoroughly with gentle agitation by hand and ultra pure water before then being submerged in an ultrasonic cleaner for 15 mins at room temperature. An oven set to 100^{o}C was used to dry out the potato peel, where it remained in residence for 12 hours until crispy and brittle. Further the potato peel waste was then crushed into a fine powder by first a pestle and mortar by hand until chunks were roughly a couple of millimetres in diameter, and then secondly by a ball mill for 30 minutes, until the dried potato peel(DPP) was a fine powder with no pieces $>$ 1mm in diameter. Any DPP that would not reduce to a sufficiently small size was manually filtered out using a sieve.

DPP was then shovelled into a ceramic boat, before being inserted in a 10mm quartz glass reaction vessel which was then itself inserted in the tube furnace for pyrolysis. Nitrogen gas at a flow rate of 500ml/minute, was passed through the DPP containing quartz glass tube to create the inert atmosphere required for carbonisation. The DPP was pyrolysed at 600^{o}C for 2.5 hours with a ramp rate of 10^{o}C/min

The experimental setup was adjusted for the carbon activation to allow for the nitrogen gas flow to first pass through the distilled water in the bubbler. As the nitrogen gas flow bubbled through the distilled water, it would carry with it water vapour causing steam activation of the potato peel biochar. Given the nature of the gas source to bubbler setup, it was difficult to determine the exact mass of steam that passed through the quartz glass reaction vessel. The potato peel biochar was activated at 700^{o}C for 1 Hour at a ramp rate of 25^{o}C/min.

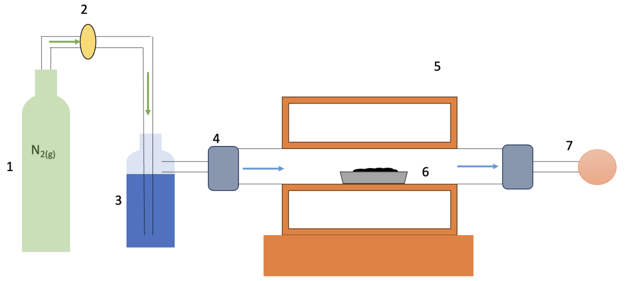


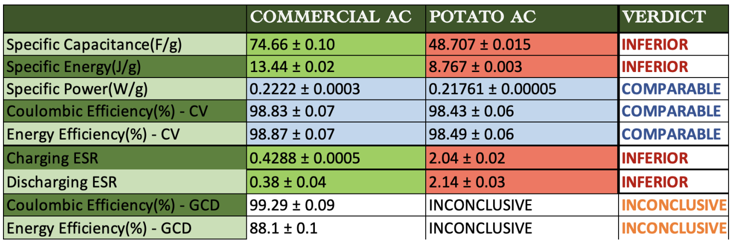
FIG. 2: Diagram of experimental setup for Activation, arrows represent direction of gas flow: 1)N_2 gas pipeline for inert conditions 2)Valve and mass flow controller, controlling flow of gas through system 3)Bubbler to bubble N_2 gas flow through ultra pure water 4)Quartz glass reaction tube inserted through tube furnace 5)Tube furnace with controllable temperature ramp rate 6)Ceramic boat containing sample 7)Gas passed into fume hood.

For the production of the activated carbon cloth electrodes using the commercially produced AC, 250mg of the AC was mixed with 12.5mg of carbon black conductive additive. Carbon black is used, as alone, the activated carbon is not conductive and would not act as an effective electrode, and thus it is mixed in solution at a 1:20 ratio to the potato peel AC. 5ml of ethanol was added to the mixture and mixed on a hot plate at $30^{o}C$ to homogenise the mixture for 1 hour until a thick slurry remained. 16 μL (micro litres) of polytetrafluoroethylene(PTFE) was added to solution to act as a binder and a pestle and mortar used for 10 minutes to fully mix the solution before being rolled out using a rolling pin on a hot plate. The putty like substance was continually rolled out and folded, until a cohesive sheet was present. Using a set of shims, the AC cloth was rolled out to $75\mu m$ thickness, and after being left to dry for 24 hours, circular electrodes 15mm in diameter were cut out of the material using a punch. Likewise for the production of the activated carbon cloth using the potato peel derived activated carbon, the same ratio of activated carbon to carbon black and PTFE was used. Given that a 10mm quartz glass reaction vessel was used due to the inner diameter of the tube furnace, 3 successive rounds of carbonisation and activation were carried out resulting in 70mg of activated carbon, meaning adjustments had to be made from the original method to the quantities of PTFE and Carbon Black added to the mixture. After being weighed, the AC electrodes formed part of the assembly of the EDLC test cell using 6M Potassium Hydroxide (KOH) as the electrolyte with a 20mm glass fibre disk soaked in KOH separating the electrodes

The potato peel derived activated carbon EDLC test cell was assembled in an identical fashion to that way which the commercially produced activated carbon EDLC test cell was and thus any similarities or differences between the electrochemical performance of both cells was due to differing quality of the activated carbon used.

IV. RESULTS

To analyse the electrochemical performance of the EDLC test cells Cyclic Voltametry(CV) and Galvanostatic Charge/Discharge (GCD) were used. CV was performed at 3 different scan rates for each test cell: 5mV/s ,15mV/s and 25mV/s. Subsequently, GCD was performed on the test cell using a charge rate of 1 Amp per Gram (A/g) up to a voltage of 0.6V. The initial testing was performed on a test cell assembled using the industrially produced, commercially available AC, to create a benchmark for EDLC performance to compare with the potato peel derived AC EDLC. The results of the following tests can be found in Fig.3, with a verdict of comparison between the commercial AC EDLC test cell and the potato AC EDLC test cell in the final column.



	COMMERCIAL AC	POTATO AC	VERDICT
Specific Capacitance(F/g)	74.66 ± 0.10	48.707 ± 0.015	INFERIOR
Specific Energy(J/g)	13.44 ± 0.02	8.767 ± 0.003	INFERIOR
Specific Power(W/g)	0.2222 ± 0.0003	0.21761 ± 0.00005	COMPARABLE
Coulombic Efficiency(%) - CV	98.83 ± 0.07	98.43 ± 0.06	COMPARABLE
Energy Efficiency(%) - CV	98.87 ± 0.07	98.49 ± 0.06	COMPARABLE
Charging ESR	0.4288 ± 0.0005	2.04 ± 0.02	INFERIOR
Discharging ESR	0.38 ± 0.04	2.14 ± 0.03	INFERIOR
Coulombic Efficiency(%) - GCD	99.29 ± 0.09	INCONCLUSIVE	INCONCLUSIVE
Energy Efficiency(%) - GCD	88.1 ± 0.1	INCONCLUSIVE	INCONCLUSIVE

FIG. 3: Using CV, the commercial AC test cell was found to have a specific capacitance 74.66 ± 0.10F/g, specific energy 13.44 ± 0.02J/g and specific power 0.2222 ± 0.0003 with a coulombic efficiency of $(98.83 \pm 0.07)\%$ and an energy efficiency of $(98.87 \pm 0.07)\%$. Using GCD it was found that the same test cell had a coulombic efficiency $(99.29 \pm 0.09)\%$ and the energy efficiency was $(88.06 \pm 0.11)\%$ with a charging ESR of $(0.4288 \pm 0.0005)\Omega$ and a discharging ESR of $(0.38 \pm 0.04)\Omega$. Then the same testing procedure for the potato AC EDLC test cell yielded a specific capacitance (48.707 ± 0.015)F/g, a specific energy (8.767 ± 0.003) J/g and a specific power (0.21761 ± 0.00005) W/g with coulombic efficiency at $(98.43 \pm 0.06)\%$ and energy efficiency at $(98.49 \pm 0.06)\%$. Using GCD in the same way, impossible results were obtained and thus the verdict of comparison was inconclusive.

A possible reason for the differing values for efficiencies from each test, when both were performed on the same test cell is that GCD directly involves energy transfer between the electrochemical system and an external circuit. Energy losses can occur due to resistive heating, polarization, and inefficiencies in the electrochemical reactions themselves. CV provides information about the reversible redox processes and capacitive behavior of the system. When performing CV it may not directly involve energy exchange with an external circuit in the same way that GCD does.[12] While CV can provide insights into the electrochemical performance of materials, it might not directly give you information about energy efficiency in the same manner as GCD measurements.

When GCD was carried out initially on the Potato AC test cell, with a charging and discharging current of 1 A/g up to a voltage of 0.6V, the specific parameters appeared to yield erroneous data. Subsequent repeats of the GCD on the potato peel test EDLC test continued to yield erroneous data. The coulombic efficiency was found in each of the 3 repeat tests to be $(100.2 \pm 0.1)\%$, $(100.9 \pm 0.1)\%$ and $(100.3 \pm 0.1)\%$ and the energy efficiencies $(107.17 \pm 0.03)\%$, $(100.5 \pm 0.5)\%$ and $(104.5 \pm 0.3)\%$ respectively. Intuitively, the results are physically impossible given that an efficiency greater than 100% would imply that the EDLC is outputting more energy than it has had inputted which would be a violation of the conservation of energy and thus is impossible. Thereby it is likely the error was due to equipment error. The most likely error was that the sampling rate of the Raspberry Pi computer used for GCD was not high enough causing key data points to be missed. Thus the GCD testing was repeated on a PalmSens device that had a much higher sampling rate. The same testing procedure was repeated exactly 1 week after the original GCD testing was done with the same voltage window and charge/discharge current of 1A/g. By then plotting the data in Microsoft excel the following graph was visualised.

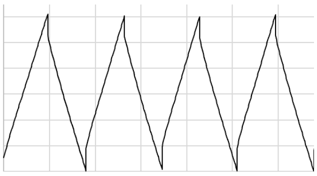


FIG. 4: Graph showing 4 complete GCD cycles(y-axis: Voltage, X-axis: time) with a voltage window of 0.6V and a charging/discharging rate of 1A/g. The ESR can be calculated using the voltage drop seen after the peaks and troughs of the graph.

Using the equation:

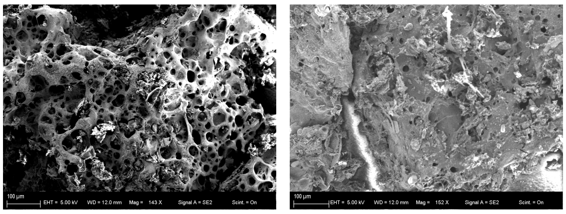
$$R_{ESR} = \frac{\Delta U}{2I}[13] \tag{1}$$

with ΔU taking the value of the mean average voltage drop observed at the charge/discharge transitions, and I taking the value 0.0202001 ± 0.0000001A, the Charging ESR and Discharging ESR were both calculated(see Fig.3).

V. DISCUSSION

The results demonstrate that potato peel emerges as a viable precursor to activated carbon with hierarchical porosity. Whilst the specific capacitance of the EDLC test cell assembled using the commercial AC had a greater specific capacitance of (74.66 ± 0.10)F/g compared to the specific capacitance of the potato peel test cell of (48.707 ± 0.015)F/g, it still does not discredit the merits of the potato peel derived activated carbon. The experimental procedure used to activate the potato peel requires much greater refinement but this could not be performed in the time frame of the project. The temperature and time for which the biomass waste is carbonised and activated for is very sensitive in terms of altering the performance limitations of the final activated carbon quality[14]. After the first complete run of potato peel carbon activation where carbonisation was completed at $500^{o}C$ for 3 hours and activation completed for 2 hours at $800^{o}C$, the result, as privately discussed, is what was referred to as 'over-activation": after steam activation had completed, there remained $<$ 5mg of substance which was a grey-blue colour. Thus in subsequent runs, to avoid the case of 'over-activation' again, a temperature of $600^{o}C$ for 2.5 hours was used for carbonisation and a temperature of $700^{o}C$ for 1 hour was used for physical activation with steam. Through 3 repetitions of the carbonisation-activation procedure, a sufficient quantity of activated carbon was obtained to create the activated carbon cloth. This method allowed for an EDLC test cell to be constructed from potato peel derived activated carbon, but no further experimentation was carried out to find the optimum conditions for the carbonisation and activation of the potato peel. The potato peel derived AC test cell did however have a specific power of (0.21761 ± 0.00005)W/g which was the same as the specific power of the commercial AC test cell to 2 s.f. meaning that the performance was very much comparable.

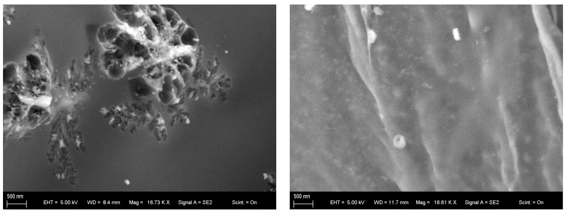
To visually analyse the porosity of the potato peel derived activated carbon, scanning electron microscopy(SEM) was used to image the varying size scales of pores in the carbon structure from macropores($>$ 50nm) to micropores($<$ 2nm). Images were taken of both the dried potato peel that had been only pyrolysed at 600^{o}C and the dried potato peel that had been pyrolysed at 600^{o}C and also physically activated by steam at 700^{o}C. The images below show the difference in the carbon structure.



(a) Image of the dried potato peel after carbonisation and activation displaying the macropores.

(b) Image of the potato peel after carbonisation only displaying the macropores of the structure

FIG. 5: Images showing the macroporous structure of the carbon post-carbonisation (b) and post-carbonisation and post-activation(a)



(a) Image of the dried potato peel after carbonisation and activation displaying the microporosity.

(b) Image of the potato peel after carbonisation only displaying the micropores of the structure

FIG. 6: Images showing the microporous structure of the carbon post-carbonisation (b) and post carbonisation & activation(a)

In Fig.5 (b) the initial development of the pores can be seen at a macroscopic level with pores visible on the surface due to the heat from pyrolysis causing the start of porosity within the carbon structure. The porosity, however, can visually be seen to be more plentiful and "sponge-like" in Fig.5 (a) where the carbon has been also activated, highlighting how the steam has reacted with the defect sites in the carbonised potato peel and has caused more of the sample to evaporate away. The extent to which the structure has been activated cannot be determined from just the one image. In Fig.6(a) it can be seen that micropores have formed in the carbon structure which serves as evidence, in conjunction with the results from the electrochemical analysis, that the potato peel is a valid precursor to activated carbon with hierarchical porosity, as the microporosity is required to get any capacitive performance from the EDLC test cell. Fig.6 (b) shows the potato peel that was only carbonised, had no visible microporosity in the particular region of the sample that was imaged at this resolution, suggestive that microporosity develops in the activation stage and not in the carbonisation stage.

Further analysis of the activated carbon structure was carried out using energy dispersive x-ray(EDX) analysis. EDX is a form of elemental analysis that calculates the elemental composition of the sample based on the characteristic x-rays of each of the elements present[17]. See below a colour coded image of a region of the activated carbon sample that was mapped using EDX.

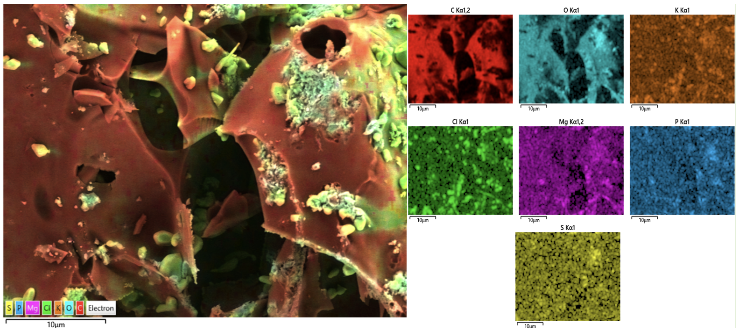


FIG. 7: Elemental map of a region of activated carbon sample: carbon=red, oxygen=turquoise, potassium=dark orange, chlorine=green, magnesium=pink, phosphorus=blue, sulphur=yellow

From a visual examination of Fig.7, the majority of the sample can be seen to be carbon with a considerable amount of potassium and chlorine present in lumps together, possibly indicative of a reasonable amount of potassium chloride present which is agreeing with expected composition of potatoes being that they are naturally high in potassium.[18] The exact proportion of each of the elements available could not be calculated due to there being only one x-ray detector on the electron microscope at the time of data collection, which caused a considerable amount of shadowing, where shadowing is the blocking of signal from the material due to the topography of the surface. Therefore, the elemental composition of the surface was mapped(see Fig.7) but the % proportion of each of the elements present could not be exactly calculated.

VI. CONCLUSIONS

Conclusively, given that the performance of the potato peel derived AC test cell had comparable specific power, coulombic and energy efficiency and also a reasonably similar specific energy and capacitance to the commercial AC test cell, potato peel does in fact present itself as a high performing precursor material for AC to be used in EDLCs. Given that potato peel is so abundantly available: in the UK alone approximately 4.4million whole potatoes are thrown away daily [5], using potato peel for industrial scale production, if the process were done efficiently, could be a plentiful, sustainable source of green energy storage technology. To make the process more efficient, reviewing and continuing the investigation to evaluate the effect of varying hold temperature, temperature ramp rate and hold time during the activation and carbonisation steps could yield a greater specific capacitance in the final EDLC test cell given the effect of varying conditions on the porosity of the activated carbon [14] [15][16] [19].

VII. FURTHER WORK

Given that the project was completed in the short time frame of 6 weeks, there were alternative routes for the project, that took a more energy conscious approach, that could not be explored. A method that could hold potential, based on the literature, is using a microwave, as opposed to conventionally using a tube furnace, for physical activation of potato peel to create AC with hierarchical porosity. This would be a highly efficient technique compared to conventional heating methods. Due to the fact that microwaves heat substances more uniformly, efficiencies of 80-85% can be achieved [20], resulting in significantly reduced pyrolysis and activation times. While pyrolysing and activating a small food waste sample in a tube furnace took up to eight hours, microwave technology could allow for the pyrolysis and activation of larger food waste samples in less than an hour. For the one-step activation of carbon from 5.0g dried bamboo impregnated with phosphoric acid was completed in 20 mins at 350W [22]. This expedited process would have not only contributed to the sustainability of the production method but also improved overall productivity. For further experimentation the possibility of microwave radiation leakage must be appropriately dealt with. The following diagram shows a potential experimental setup.

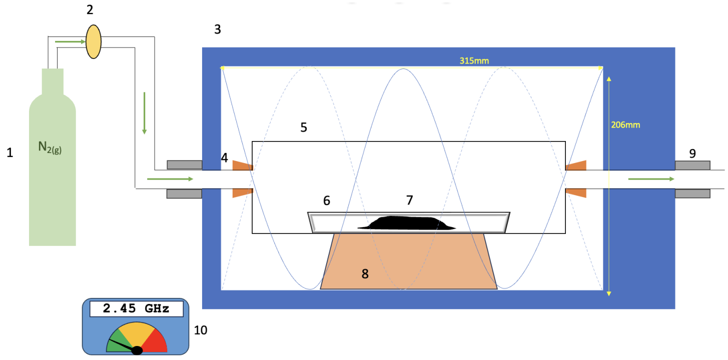


FIG. 8: Diagram of experimental setup for microwave assisted activation. 1) Source of inert gas (Nitrogen Gas supply), 2) Valve and mass flow controller for nitrogen gas pipeline, 3) Panasonic Inverter Microwave Oven, 4)Tube bung connecting silicon pipe and reaction chamber, 5)Quartz reaction vessel, 6)Crucible, 7)Cleaned and dried biomass food waste sample, 8)Ceramic stage, 9)100mm of aluminium casing around tube, 10) Frequency detector

Additionally, refinement of the original method should be completed. Whilst the conditions that were used (carbonisation at 600^oC for 2.5 hours and activation at 700^oC for 1 hour) had been successful in creating activated carbon with hierarchical porosity, further investigation could identify at which carbonisation and activation temperatures the highest surface area would be obtained for Maris Piper potato peelings. Further, the length of time of each of the steps should be studied to find what length of time would be the most optimal.

ACKNOWLEDGMENTS

The author would like to thank Rhys Williams, for providing wisdom throughout the project and teaching the standard method of AC electrode production.

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