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Influence of Porosity Tuning in Magnesium Citrate-Derived Carbon Composites on Electrochemical Supercapacitor Performance

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ABSTRACT

The growth in energy demand and the instability of renewable sources necessitate the development of effective energy storage systems. Supercapacitors are promising devices due to their high power, fast charging and discharging, and long cycle life. This paper investigates the structural and electrochemical properties of templated carbons produced from the carbonization of magnesium citrate and its composites with polyvinyl alcohol (PVA). It has been established that carbon from pure magnesium citrate is characterized by a developed porous structure with a specific surface area of 1706 m²/g and a microporous volume of 0.624 cm³/g. The addition of PVA leads to a decrease in specific surface area (to 514 m²/g at 66% PVA) and a fine tuning of the degree of structural order, which is confirmed by Raman spectroscopy data. Electrochemical tests in a two-electrode cell using 5 M NaNO₃ showed a maximum specific capacitance of 128 F/g for carbon derived from pure magnesium citrate at 1.6 V. Composite materials demonstrate lower capacitance but maintain high Coulombic efficiency (>95%) within the tested voltage windows. These results indicate that the incorporation of PVA reduces both the accessible surface area and the electrochemical performance compared with pure magnesium citrate derived carbon, while confirming the promise of magnesium citrate as an affordable precursor for the production of porous carbon materials for supercapacitors.

1. Introduction

The growth in global energy demand necessitates the widespread introduction of renewable energy sources such as wind, wave and solar power. However, these sources are characterized by unstable generation, which requires the development of effective energy storage and conversion technologies, including for mobile applications [1-3]. Among existing electrical energy storage systems, electrochemical capacitors, or supercapacitors (SC), occupy a special place, as they are most effective in modes of rapid accumulation and high-power delivery. In this regard, the creation of highly efficient and environmentally friendly SC is one of the priority areas for the development of modern energy storage systems [4, 5].

A supercapacitor is an electrochemical device in which charge is stored by forming an electric double layer (EDL) at the interface between materials with electronic and ionic conductivity. Unlike rechargeable batteries, SC operate primarily through the charging and discharging of the EDL on polarized electrodes with a developed specific surface area [6]. These processes are reversible and can be repeated up to hundreds of thousands of cycles, with each cycle lasting a fraction of a second. Supercapacitor electrodes are made of porous materials with a high specific surface area [7]. Carbon nanomaterials are most widely used as electrode structures due to their high corrosion resistance, good electronic conductivity, thermal stability, and developed porous structure. The pore size of the material is of significant importance: excessively large pores reduce the active surface area,

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while pores that are too small prevent electrolyte ions surrounded by a solvate shell from effectively penetrating the pores. According to the literature, the optimal pore size is 1–5 nm [8].

Activated carbons, including those obtained from wood [9] or rice husks [10, 11], activated carbon fibers [12], carbide-derived carbons [13], templated carbon structures [14, 15], carbon nanotubes [16], carbon nanohorns [17], onion-like carbon and carbon foams [18, 19] are widely used as electrode materials. These materials can achieve specific capacitances of several hundred F/g when their specific surface area exceeds 1000 m²/g. However, many of them are characterized by high production costs. Safe and affordable methods for synthesizing porous carbon materials are currently being actively developed [20]. Traditional methods of producing activated carbons do not allow precise control of the morphology and distribution of pores. To solve this problem, template synthesis methods are used, which ensure the formation of mesoporous structures with specified parameters [14].

A promising direction is the creation of new porous carbon materials for supercapacitor electrodes, combining high specific capacitance, optimal texture characteristics and low cost. In this regard, the aim of this work is to develop porous carbon materials for use as SC electrode structures, as well as to study the dependence of their specific capacitance on texture parameters and the type of carbon used. It should be noted that synthesis using micellar templates is technologically complex and requires expensive organic reagents [21]. A more accessible alternative is template synthesis using solid templates that are removed after the carbon structure is formed. This method allows for variation in pore size, but is associated with difficulties in selecting a suitable template [22].

The literature describes methods for obtaining carbon materials using mesoporous silicon dioxide as a solid template, but its removal is a costly stage of the process [23]. Oxides of other metals can be used as an alternative. Recently, an approach has been proposed in which solid template particles are formed in situ from precursors (magnesium citrate and acetate) directly during the synthesis of mesoporous carbon [14]. However, published works do not discuss the mechanism of oxide templating in detail, and the concentrations of precursors are not optimized. Thus, the tasks of finding effective solid templates and optimizing the conditions for the synthesis of mesoporous carbon materials remain relevant [24].

In this work, to reduce production costs, control

porosity and simultaneously improve the physico-chemical properties of electrodes, the modification of magnesium citrate based templated carbons with polyvinyl alcohol (PVA) is investigated. PVA is an inexpensive, environmentally friendly, and thermally stable polymer that can act as a binder and carbon precursor. Although PVA is often hypothesized to influence pore development during carbonization, its actual effect depends strongly on synthesis conditions. Thus, studying the effect of the magnesium citrate to PVA ratio on the structural and electrochemical characteristics of carbon composites allows not only reducing the cost of the material, but also to determine the influence of optimal precursor composition on the capacitive characteristics of SC.

2. Experimental part

2.1. Materials

Magnesium citrate (MC, chemically pure), polyvinyl alcohol (PVA, chemically pure), and 60% aqueous emulsion of polytetrafluoroethylene (PTFE) were purchased from Sigma-Aldrich. Hydrochloric acid (HCl, chemically pure) and sodium hydroxide (NaOH, chemically pure) were supplied by Labopharma. Whatman GF/A glass fiber filter and TIMCAL SUPER C45 conductive carbon black were used as received. All chemicals were used without further purification.

The composite precursor mixtures denoted as MC:PVA33%, MC:PVA50%, and MC:PVA66% correspond to 33 wt.%, 50 wt.%, and 66 wt.% PVA, respectively, relative to the total mass of the MC+PVA mixture.

2.2. Synthesis of MC and MC:PVA derived porous carbons

MC and PVA powders were weighed according to the required mass ratios (33%, 50%, or 66% PVA) and thoroughly mixed in an agate mortar for 15 min to obtain homogeneous precursor blends. The mixtures were evenly distributed in a thin layer in porcelain boats without compaction to avoid local overheating and deformation during heat treatment.

Carbonization was carried out in a vertical furnace using a cylindrical CVD type quartz reactor. The samples were heated to 800 °C at a rate of 10 °C/min under a continuous nitrogen atmosphere (200 mL/min) and maintained at this temperature for 1 h. After carbonization, the materials were cooled to room temperature and ground into a fine powder. To remove inorganic residues and template derived by products, the powders were treated in 2 M HCl for 24 h, washed repeatedly with distilled

water until neutral pH, and dried in an oven at 70 °C for 4 hours.

2.3. Electrode preparation

The active carbon material was mixed with TIM-CAL SUPER C45 conductive carbon black and PTFE binder in an agate mortar. The components were combined in the mass ratio 85% templated carbon, 10% carbon black, and 5% PTFE. The resulting mixture was rolled manually and then using steel rollers to obtain films with a thickness of approximately 80 µm. The films were dried in a vacuum oven at 80 °C for 12 h and subsequently punched into 10 mm diameter electrodes.

2.4. Characterization methods

The microstructure and surface morphology of the carbon materials were examined using a JEOL JSM IT890 scanning electron microscope (SEM). Transmission electron microscopy (TEM) was performed using a JEOL JEM instrument. Raman spectra were recorded using a Horiba LabRAM spectrometer equipped with a 532 nm excitation laser.

Thermogravimetric analysis (TGA) was conducted using a PerkinElmer STA6000 at a heating rate of 10 °C/min under a nitrogen atmosphere.

X ray photoelectron spectroscopy (XPS) was performed using a Thermo Scientific NEXSA spectrometer with a monochromated Al K α X ray source (1486.6 eV). Survey and high-resolution spectra were collected at pass energies of 100 eV and 50 eV, respectively. Peak fitting was carried out using a Shirley background and mixed Gaussian–Lorentzian line shapes.

Electrochemical measurements were performed using cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD) methods using a Biologic SP-150E potentiostat/galvanostat. All electrochemical measurements were performed using a PSC-TWE012 Swagelok two-electrode cell. The electrodes were studied at room temperature using cyclic voltammetry with a scan rate of 2 mV/s and galvanostatic charge-discharge at a current density of 0.2 A/g in the potential range from 0.6 to 1.6 V.

Specific capacitance was calculated from GCD curves using:

$$C = \frac{4I\Delta t}{m\Delta V}$$

where: m is the mass of active material in a single electrode.

A neutral aqueous 5 M NaNO₃ solution was used as the electrolyte. Its dynamic viscosity was 1.632 mPa·s (measured using a ViscoQS 100 viscometer), pH was 7.257 (A120 laboratory pH meter), and conductivity was 187.5 mS·cm⁻¹ (A150 laboratory conductivity meter).

3. Results and discussions

3.1. Analysis of surface morphology using SEM and TEM

Scanning electron microscopy of carbon material synthesized by pyrolysis of magnesium citrate reveals a distinct multiscale morphology formed as a result of thermal decomposition and structural rearrangement of the precursor. Micrographs clearly show large fragmented agglomerates of the carbon matrix interspersed with a branched system of channels, cracks and porous voids. These features are associated with shrinkage of the material during carbonization and the removal of volatile species. A significant part of the surface exhibits a porous, foam like texture, which is typical for carbons obtained from organic precursors. Although SEM does not allow direct identification of micropores or mesopores, the presence of numerous open cavities and irregular voids is consistent with the high specific surface area and pore volumes determined by BET analysis (Table 1). In certain areas, denser compact regions are observed next to more amorphous domains, reflecting the heterogeneity of magnesium citrate decomposition and different degrees of local carbonization. The overall morphology provides accessible pathways for electrolyte penetration, which is important for electrochemical applications. SEM images are presented in Fig. 1a-c.

When studying composite materials using TEM, differences in contrast and local ordering depending on the polyvinyl alcohol (PVA) content can be observed (Fig. 2a-c).

In samples with low PVA content, the structure appears predominantly amorphous: the contrast is evenly distributed, and phase boundaries are blurred. As the proportion of PVA increases, regions with slightly more ordered or denser stacking become visible. These areas show clearer contours and periodic contrast variations, which may indicate changes in the carbon matrix caused by different precursor compositions. Since PVA does not remain as a polymer after carbonization at 800 °C, the observed features should not be interpreted as preserved PVA crystallites or hydrogen bonded macro-

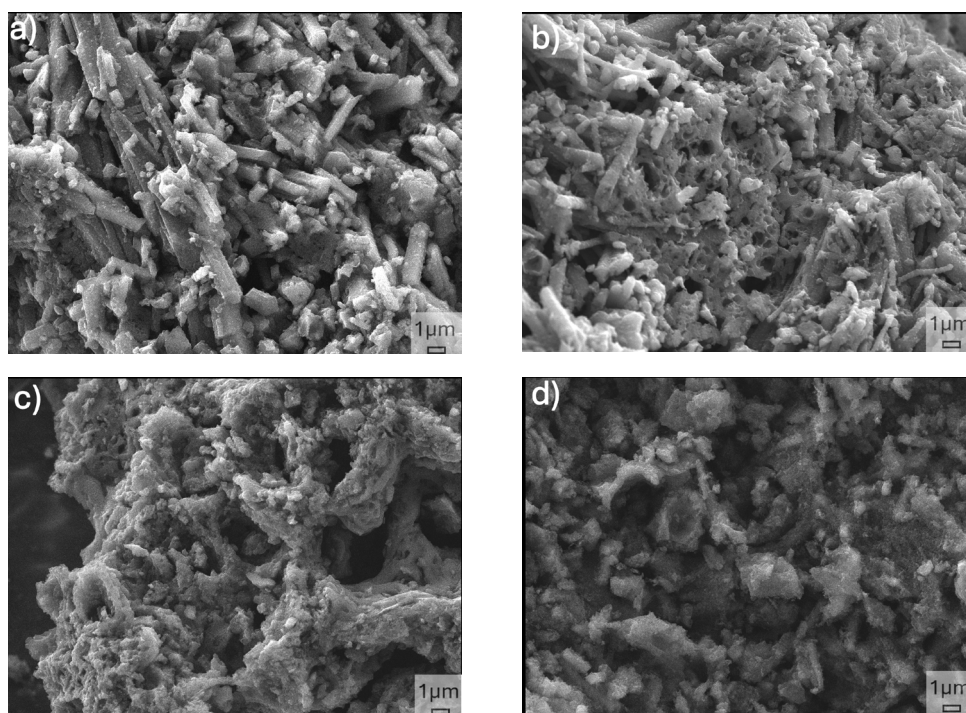


Fig. 1. SEM images of MC (a), MC:PVA33% (b), MC:PVA50% (c), and MC:PVA66% (d).

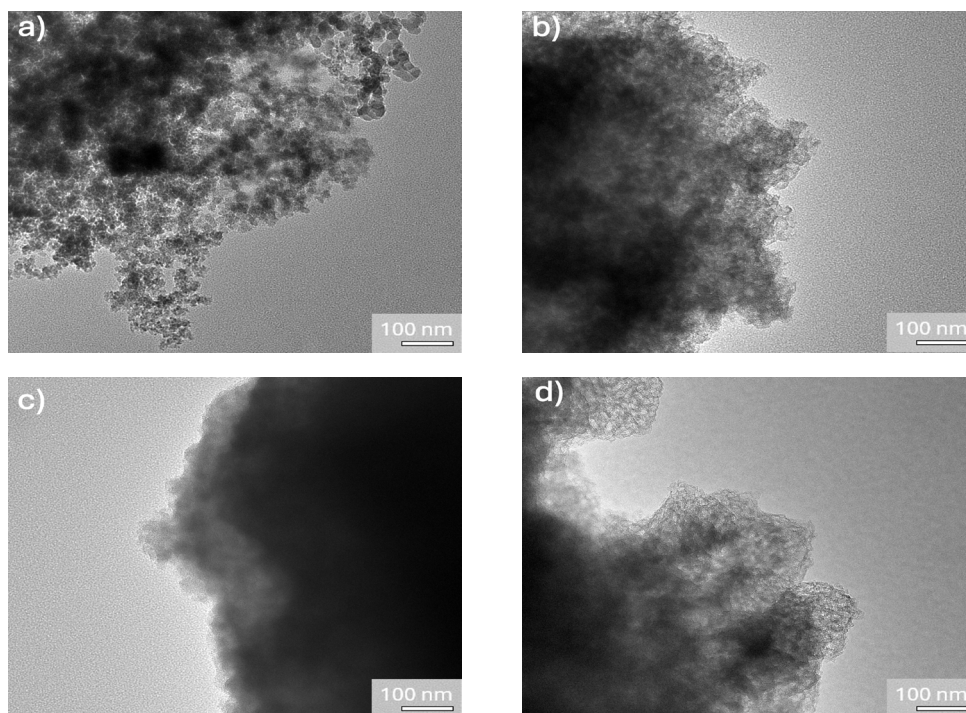


Fig. 2. TEM images of MC (a), MC:PVA33% (b), MC:PVA50% (c), and MC:PVA66% (d).

molecular chains. Instead, the contrast differences likely reflect variations in carbon domain size, local ordering, and residual oxygen containing groups formed during carbonization. Thus, TEM analysis shows that increasing the initial PVA content influences the internal morphology of the resulting carbon, although the structure remains largely amorphous.

3.2. BET porosimetric analysis

Nitrogen (N_2) sorption isotherms at 77 K were measured using a Nova 600 Surface Area and Porosity Analyzer (Anton Paar, Austria). The specific surface area was determined by the Brunauer-Emmett-Teller (BET) method. Pore size distribution and pore volume were evaluated using non-local densi-

ty functional theory (NLDFT) in the Kaomi for Nova software. Prior to the measurements, all samples (~50 mg) were degassed at 200 °C for 15 h.

The results show that the specific surface area of the pure MC derived carbon is 1706 m²/g, as indicated in Table 1, confirming the presence of a highly developed porous structure. The high correlation coefficient ($r = 0.999$) further confirms the accuracy of the isotherm fitting and the reliability of the BET calculations. The BET constant $C = 104.4$ suggests strong interaction between nitrogen and the carbon surface. According to Table 1, the addition of PVA leads to a systematic decrease in S_{BET} , micropore volume, mesopore volume, and total pore volume, reaching 514 m²/g for the MC:PVA66% sample. This trend is central to the interpretation of electrochemical performance, as lower surface area and reduced pore volume correlate with the lower specific capacitance observed for composite samples. This confirms that PVA addition reduces the accessible surface area and pore network contributing to EDL formation.

The pore size distribution and nitrogen adsorption-desorption isotherms (Fig. 3a, b, c) further confirm the hierarchical porous structure of the obtained material. As shown in Fig. 3a, all samples exhibit a dominant mesopore peak in the range of ~3-6 nm, which is consistent with the average pore

sizes listed in Table 1 (6.0 nm for MC, 6.0 nm for MC:PVA33%, 5.5 nm for MC:PVA50%, and 5.6 nm for MC:PVA66%). Although the exact average pore size slightly varies among the samples, the overall pore size distribution profile remains similar, with mesopores being the major contribution and micropores present only in minor amounts. Figure 3b demonstrates a typical type IV isotherm with a noticeable hysteresis loop, indicating the presence of mesopores. Thus, the results of the BET analysis demonstrate that pure MC derived carbon possesses the most developed porous structure, while PVA addition reduces porosity and surface area, which directly affects electrochemical behavior.

3.3. Raman spectroscopic analysis

Figure 4 shows Raman spectra of MC samples and MC:PVA composites with PVA contents of 33%, 50% and 66% in the range of 500-3000 cm⁻¹. Two characteristic bands are observed in all samples studied: the D band in the region of ~1350 cm⁻¹ and the G band near ~1580-1600 cm⁻¹, which is typical for carbon materials. The D band is associated with structural defects in the carbon matrix, while the G band corresponds to vibrations of sp² hybridized carbon bonds [25, 26].

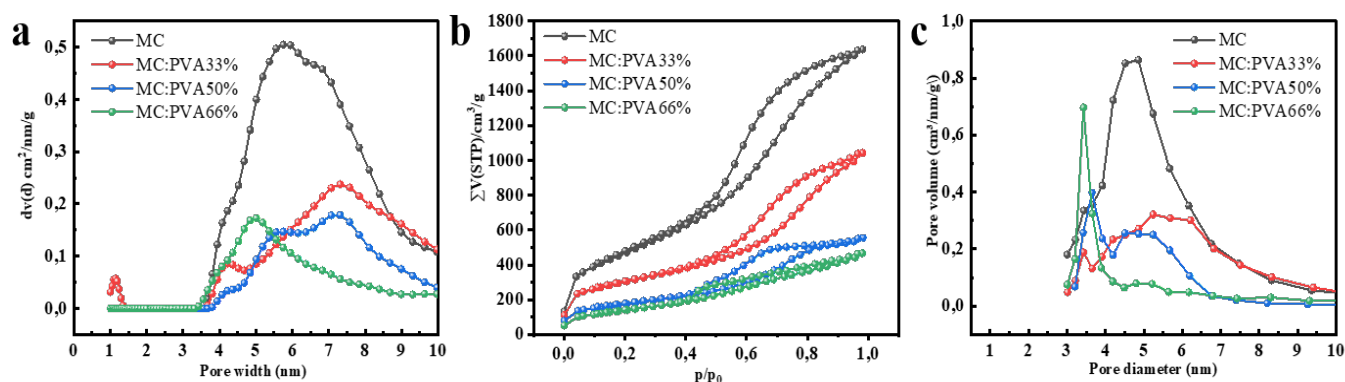


Fig. 3. Templated carbon of MC, MC:PVA33%, MC:PVA50%, and MC:PVA66% (a) Pore size distributions calculated by DFT, (b) N₂ adsorption-desorption isotherms and (c) BJH analysis.

Table 1. Main results of the BET analysis

Sample	S_{BET} (m ² /g)	V_{micro} (cm ³ /g)	V_t (cm ³ /g)	V_{meso} (cm ³ /g)	V_{micro}/V_t (%)	Average pore, (nm)
MC	1706	0.624	2.537	2.491	24.6%	6.0
MC:PVA33%	1074	0.418	1.616	1.518	25.9%	6.0
MC:PVA50%	621	0.243	0.861	0.850	28.2%	5.5
MC:PVA66%	514	0.189	0.724	0.714	26.1%	5.6

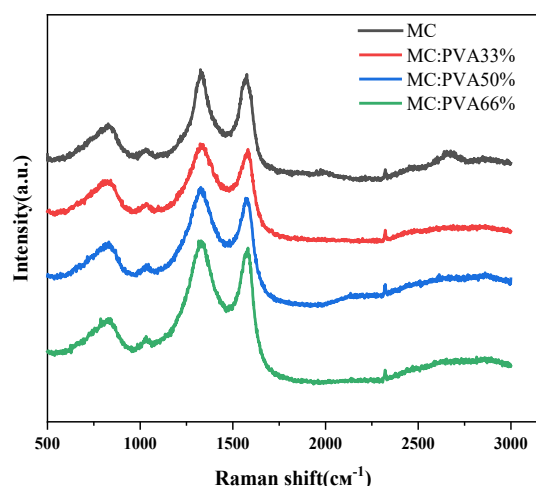


Fig. 4. Raman spectra of MC, MC:PVA33%, MC:PVA50%, and MC:PVA66%.

As the PVA content in the composite increases, changes in the intensity of these bands are observed. In particular, for the MC:PVA 66% sample, a more pronounced intensity of both the D- and G-bands is recorded compared to pure MC and samples with a lower PVA content. The I_D/I_G intensity ratio changes, indicating a redistribution of defective and ordered areas in the carbon structure. An increase in this parameter suggests a higher concentration of structural defects and a reduction in the average size of ordered sp^2 domains with increasing PVA content. The calculated I_D/I_G ratios are approximately: MC – 0.92, MC:PVA33% – 0.95, MC:PVA50% – 1.02, MC:PVA66% – 1.08.

A broad 2D band is present in the high-frequency range of 2500–3000 cm^{-1} . It is more pronounced in pure MC sample, which may indicate slightly higher ordering of sp^2 domains. As the PVA content increases, the intensity of the 2D band decreases and its shape becomes more diffuse.

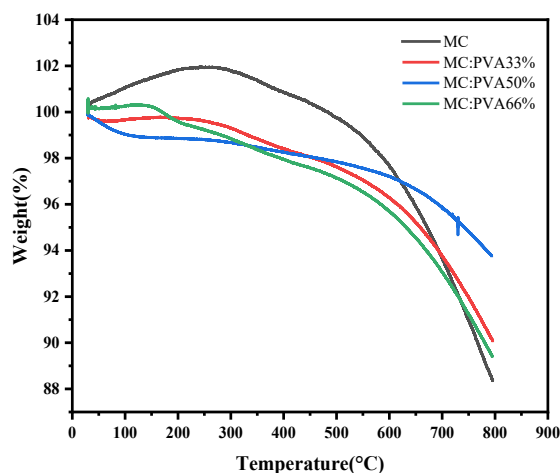


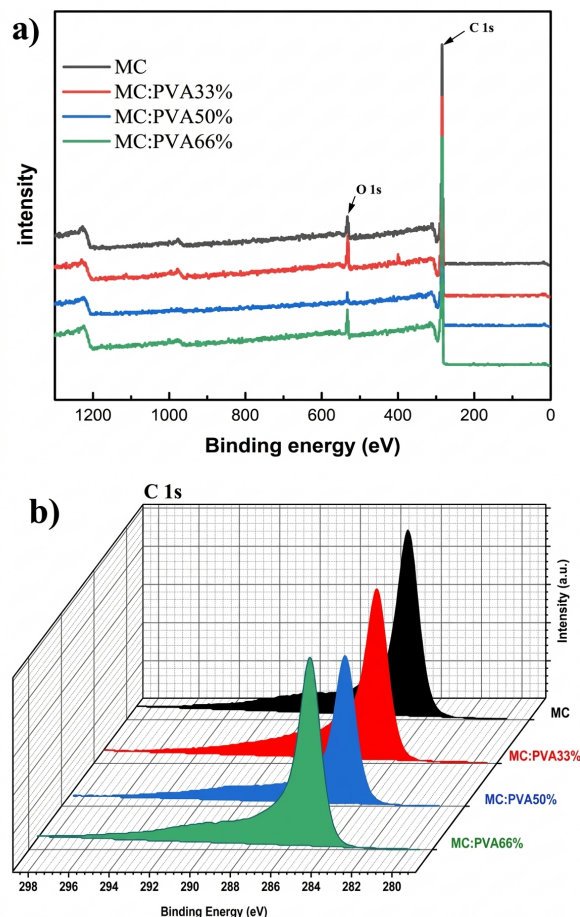
Fig. 5. TGA curves of MC, MC:PVA33%, MC:PVA50%, and MC:PVA66% under N₂ atmosphere.

Thus, Raman analysis demonstrates that the introduction of PVA affects the structural characteristics of the carbon matrix, changing the balance between defective and ordered areas, and increasing the proportion of disordered carbon.

3.4. Thermogravimetric analysis

Thermogravimetric analysis (Fig. 5) shows that the nature of thermal decomposition depends on the PVA content in the MC:PVA composition. For the MC sample, relatively high thermal stability with insignificant mass change is observed in the range up to ~500–550 °C. Above 600 °C, mass loss occurs due to the removal of residual oxygen containing groups and further rearrangement of the carbon matrix. The residual mass at 800 °C is about 88–89%.

The introduction of PVA modifies the thermal behavior. The MC:PVA33% sample shows a slightly earlier onset of mass loss compared to pure MC but demonstrates a higher residual mass at elevated temperatures. The most pronounced increase in thermal stability is observed for the MC:PVA50% composition, which loses mass more slowly above ~650 °C and reaches a residual mass of ~93–94% at



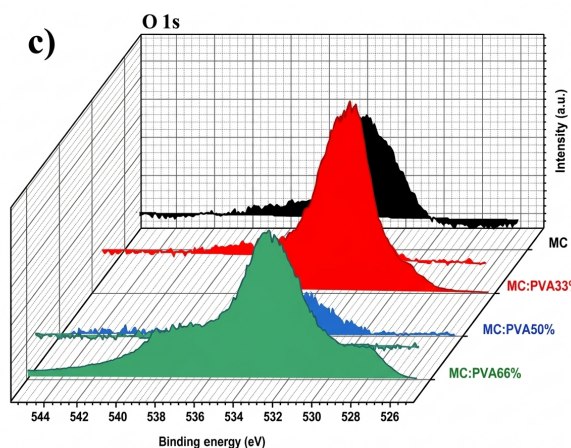


Fig. 6. XPS spectra of MC, MC:PVA33%, MC:PVA50%, and MC:PVA66% (a-c).

800 °C. With a further increase in PVA content to 66%, accelerated mass loss and reduced thermal stability are observed compared to the 50% PVA sample.

Thus, the TGA results indicate that the MC:PVA50% composition exhibits the highest thermal stability within the studied series. This conclusion refers only to thermal behavior, as pure MC remains superior in textural and electrochemical performance.

3.5. XPS analysis

Figure 6a shows overview XPS spectra of MC samples and MC:PVA composites with PVA contents of 33%, 50% and 66%. All samples exhibit two main peaks at ~285 eV (C 1s) and ~531-533 eV (O 1s), respectively. Survey spectra show no detectable surface impurities within the sensitivity limits of XPS. As XPS probes only the top few nanometers, this observation refers to surface cleanliness rather than bulk chemical purity. Magnesium related signals (Mg 1s, Mg 2p) were not observed, indicating effective removal of magnesium species after HCl treatment.

In the C 1s spectra (Fig. 6b), the dominant peak at ~284.6-285.0 eV corresponds to C–C/C–H bonds. Composite samples show a slight shift of the C 1s peak towards higher binding energies, which is attributed to the increased presence of oxygen-containing groups (C–O, C=O, O–C=O) formed during carbonization of MC:PVA precursors. This shift should not be interpreted as hydrogen bonding between MC and PVA, since PVA does not remain as a polymer after carbonization at 800 °C.

The O 1s spectra (Fig. 6c) exhibit broad asymmetric peaks in the range of 530-533 eV, indicating several oxygen chemical states. The gradual increase in O 1s intensity with increasing PVA content confirms the

higher concentration of oxygen-containing groups in the composite materials.

3.6. Electrochemical Performances

A Swagelok two-electrode cell was assembled to evaluate the electrochemical characteristics of the material. Stainless steel (SS) electrodes were used as current collectors. The manufactured electrode films were cut into 10 mm discs. The mass used for normalization corresponds to the active material mass of one electrode. The first carbon electrode was placed on the SS current collector, wetted with 5 M NaNO₃ electrolyte, covered with an electrolyte soaked separator, and then the second electrode was installed. The cell was hermetically sealed and connected to a BioLogic potentiostat/galvanostat for electrochemical testing [10].

Before studying the composite samples, electrodes made of pure magnesium citrate were tested. Electrochemical measurements were performed using cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD). CV was carried out in voltage windows of 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6 V at a scan rate of 2 mV/s. GCD tests were performed at a current density of 0.2 A/g within the same voltage windows.

Figures 7 and 8 show CV and GCD curves for MC and MC:PVA composites (33%, 50%, 66%). The color coding is consistent: MC – black, MC:PVA33% – red, MC:PVA50% – blue, MC:PVA66% – green. Figure 7 illustrates how the shape of the CV curves evolves with increasing potential window. As the voltage increases, the CV loops widen, indicating a rise in capacitance. The incorporation of PVA leads to more rectangular profiles and higher currents, reflecting an improved and more stable capacitive response compared to pure MC. Figure 8 presents the corresponding GCD curves at different upper voltage limits. MC shows a longer discharge time, whereas MC:PVA composites discharge more rapidly. With increasing PVA content, the discharge profiles become shorter, pointing to a decrease in specific capacitance and higher internal resistance. The capacitance and Coulombic efficiency values are presented in Table 2.

A comparative analysis shows that MC:PVA33% exhibits lower electrochemical characteristics than MC:PVA50%, which is reflected in Table 2. At the same time, MC:PVA33% demonstrates more uniform CV loops and longer discharge times in GCD profiles, which may indicate differences in ion transport or electrode wetting.

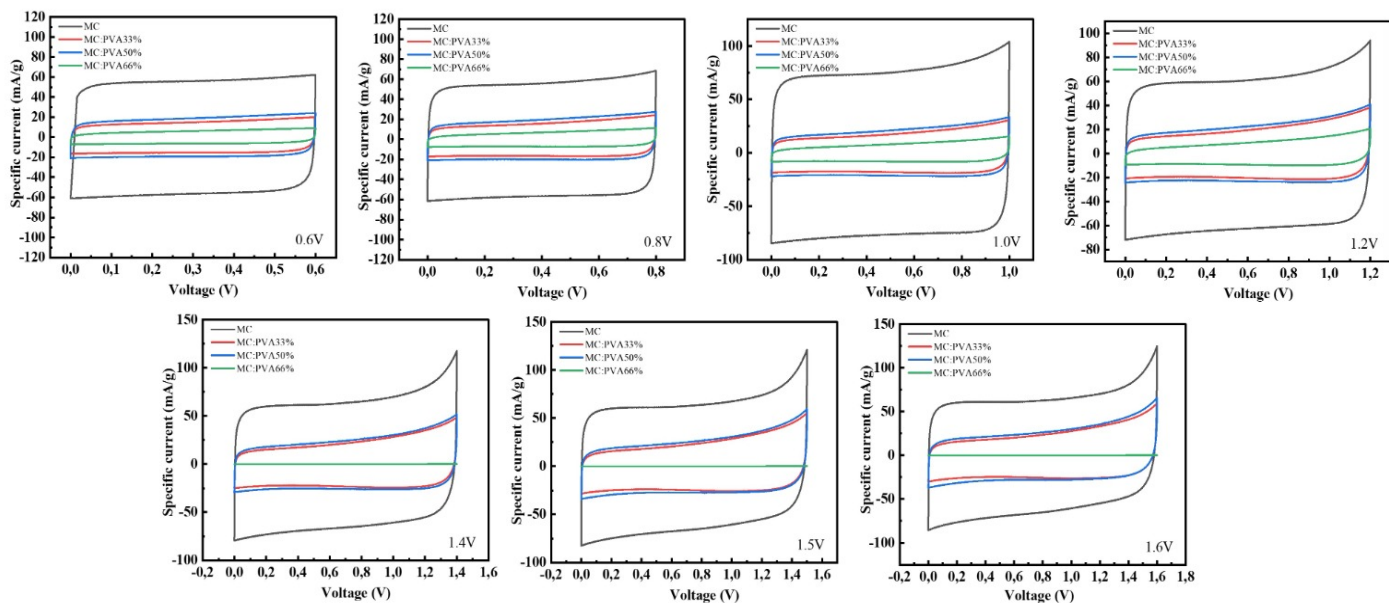


Fig. 7. CV curves of the MC, MC:PVA33%, MC:PVA50%, and MC:PVA66% electrodes recorded in 5 M NaNO₃ electrolyte at a scan rate of 2 mV/s.

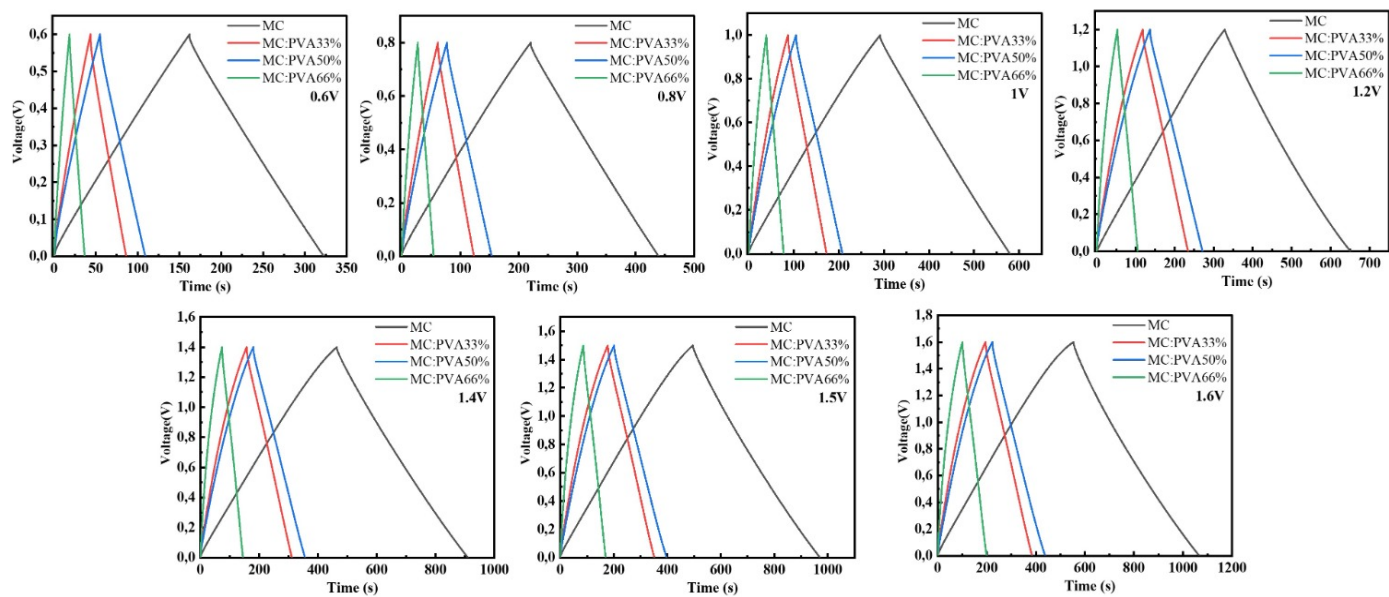


Fig. 8. GCD curves of the MC, MC:PVA33%, MC:PVA50%, and MC:PVA66% electrodes recorded in 5 M NaNO₃ electrolyte at a current density of 0.2 A/g.

Table 2. Electrochemical characteristics based on GCD data

Voltage window, V	MC		MC:PVA33%		MC:PVA50%		MC:PVA66%	
	C, F/g	Eff, %	C, F/g	Eff, %	C, F/g	Eff, %	C, F/g	Eff, %
0.6	107	99.5	28	99.6	36	99.5	12	99.5
0.8	110	99.2	31	99.4	38	99.3	14	99.4
1.0	115	98.7	34	99.1	41	99.1	15	99.2
1.2	107	98.0	39	98.6	45	98.7	17	98.9
1.4	127	96.1	44	98.1	50	98.1	20	98.3
1.5	125	95.6	46	97.7	52	97.7	22	98.2
1.6	128	92.8	47	97.5	54	97.0	24	98.1

Table 2 shows that the introduction of PVA decreases the specific capacitance compared to pure MC. This decrease is substantial, especially at 1.6 V, where MC reaches 128 F/g, while MC:PVA33%, MC:PVA50%, and MC:PVA66% show 47, 54, and 24 F/g, respectively. MC:PVA50% can be considered the best composite sample, but pure MC remains the best-performing material in the entire series.

4. Conclusion

The study examined how the quantitative ratio of magnesium citrate and polyvinyl alcohol affects the structural and electrochemical properties of the resulting carbon composites. A lower magnesium citrate content leads to reduced capacitive performance due to a smaller carbon phase fraction and poorer conductivity after carbonization.

BET analysis of the carbon derived from pure magnesium citrate showed a high specific surface area of 1706 m²/g ($r = 0.999$, $C = 104.4$), indicating a well developed porous structure with strong nitrogen affinity. This sample also demonstrated the highest specific capacitance (128 F/g at 1.6 V), confirming its suitability as an active material for electrochemical energy storage.

Introducing PVA into the precursor mixture systematically decreases the specific surface area, pore volume, and electrochemical performance. Raman and XPS analyses reveal increased structural disorder and higher concentrations of oxygen containing surface groups in MC:PVA derived carbons.

Although the composite samples exhibit lower capacitance than carbon derived from pure magnesium citrate, all materials maintain high Coulombic efficiency within the tested voltage windows, indicating stable electrochemical performance. Overall, the results demonstrate that precursor composition is a key factor governing the structural and electrochemical characteristics of the resulting carbons, providing guidance for the rational design of electrode materials for supercapacitors.

Author Contributions

Zhazira Supiyeva – Conceptualization, Supervision, Writing – Review & Editing, Resources, Funding Acquisition. **Bekzat Khamzin** – Writing – Original Draft, Writing – Review & Editing, Methodology, Investigation, Validation, Data Curation. **Balaussa Balgabayeva** – Data Curation, Visualization. **Dynmukhambet Baimbetov** – Methodology, Formal Analysis. **Aigul Tugelbayeva** – Data Curation,

Visualization, Writing – Review & Editing. **Qamar Abbas** – Conceptualization, Formal Analysis, Supervision, Validation, Visualization, Writing – Review & Editing.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Влияние регулирования пористости в углеродных композитах на основе цитрата магния на характеристики электрохимического суперконденсатора

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АННОТАЦИЯ

Рост энергопотребления и нестабильность возобновляемых источников энергии требуют разработки эффективных систем накопления энергии. Суперконденсаторы представляют собой перспективные устройства благодаря высокой мощности, быстрому заряду и разряду, а также длительному сроку службы. В данной работе исследованы структурные и электрохимические свойства темплатных углеродов, полученных путем карбонизации магния цитрата и его композитов с поливиниловым спиртом (PVA). Установлено, что углерод, полученный из чистого магния цитрата, характеризуется развитой пористой структурой со специфической поверхностью 1706 м²/г и микропористым объемом 0,624 см³/г. Добавление PVA приводит к снижению удельной поверхности (до 514 м²/г при содержании PVA 66%) и тонкой настройке степени структурного порядка, что подтверждается данными рамановской спектроскопии. Электрохимические испытания в двухэлектродной ячейке с использованием 5 М NaNO₃ показали максимальную удельную емкость 128 Ф·г для углерода, полученного из чистого магния цитрата, при напряжении 1,6 В. Композитные материалы демонстрируют более низкую емкость, но сохраняют высокую кулоновскую эффективность (>95%) в исследованных диапазонах напряжений. Полученные результаты показывают, что введение PVA снижает доступную поверхность и электрохимическую производительность по сравнению с углеродом, полученным из чистого магния цитрата, одновременно подтверждая перспективность магния цитрата как доступного прекурсора для получения пористых углеродных материалов для суперконденсаторов.

Ключевые слова: накопление энергии, суперконденсатор, пористые углеродные материалы, цитрат магния, поливиниловый спирт (PVA)

Магний цитраты негізінде алынған көміртекті композиттердегі кеуектілікті реттеудің суперконденсаторлардың электрохимиялық сипаттамаларына әсері

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АҢДАТПА

Энергияға деген сұраныстың артуы және жаңартылатын энергия көздерінің тұрақсыздығы тиімді энергия сақтау жүйелерін әзірлеуді қажет етеді. Суперконденсаторлар жоғары қуаттылығы, зарядтау мен разрядтау жылдамдығы және ұзақ циклдік тұрақтылығы арқасында перспективалы құрылғылар болып табылады. Бұл жұмыста магний цитраты мен оның поливинил спиртімен (PVA) алынған композиттерін карбонизациялау арқылы синтезделген темплатты көміртектің құрылымдық және электрохимиялық қасиеттері зерттелді. Таза магний цитратынан алынған көміртектің $1706 \text{ м}^2/\text{г}$ меншікті беті және $0,624 \text{ см}^3/\text{г}$ микрокеуекті көлемі бар дамыған кеуекті құрылымға ие екені анықталды. PVA енгізу меншікті беттің төмендеуіне (PVA 66% болғанда $514 \text{ м}^2/\text{г}$ дейін) және құрылымдық реттілік дәрежесін дәл реттеуге алып келеді, бұл раман спектроскопиясы деректерімен расталды. 5 M NaNO_3 электролиті бар екі электродты ұяшықта жүргізілген электрохимиялық сынақтар таза магний цитратынан алынған көміртек үшін $1,6 \text{ V}$ кернеуде $128 \text{ Ф} \cdot \text{г}$ максималды меншікті сыйымдылықты көрсетті. Композиттік материалдар төменірек сыйымдылық көрсеткенімен, зерттелген кернеу терезелерінде жоғары кулондық тиімділікті ($>95\%$) сақтайды. Алынған нәтижелер PVA енгізу қолжетімді бет пен электрохимиялық өнімділікті төмендететінін, бірақ магний цитратының суперконденсаторларға арналған кеуекті көміртекті материалдарды өндіру үшін қолжетімді және перспективалы прекурсор екенін растайтынын көрсетеді.

Түйін сөздер: энергия жинақтау, суперконденсатор, кеуекті көміртекті материалдар, магний цитраты, поливинил спирті (PVA)