

Preparation, investigation and application of a new type of polyurethane-based nanocomposite foams

Ph.D. Dissertation Booklet

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1. Introduction

Plastics are an important material in our economy and daily lives. However, they have serious negative effects on the environment and human health. The world is facing a plastic crisis and it has become a global concern, as plastic waste is now so ubiquitous in the natural environment. About 400 million tons of plastic waste are generated annually, of which at least 10 million tons end up in the ocean [1]. Today, almost 26 million tons of plastic waste is generated in Europe every year [2] but only less than 30% of plastic is collected for recycling [3]. In 2020, the European Commission adopted the EU's new circular economy action plan showing the way to a climate-neutral, competitive economy of empowered consumers [4].

At present, the most inevitable and thriving plastic material in use is polyurethanes (PUs) with a total production of 24 million tons in 2020 and it is expected to grow to 27.61 million tons in 2026 [5]. PU consumption is expected to grow, driven by its versatility towards new applications. The wide application of PU causes its continual presence as a solid waste stream in the environment as discarded consumer and industrial products. PUs are classified as flexible foams (36%), rigid foams (32%), PU reaction injection molding and elastomers (32%) [6]. The total production of PU products in EMEA (Europe, the Middle East, and Africa) alone was reported as 6.52 million tonnes in 2019, out of which 8% are PU elastomers [7]. PU elastomers are high-performance materials with a wide range of applications such as films, elastic fibres, medical tubes and shoe soles [8]. They also find applications in other industrial sectors such as the construction, aerospace and automobile industries due to their large elastic deformation and excellent noise and vibration damping capabilities. Their extensive usage results in the generation of a large number of scrap materials, which is not immediately degradable.

The generated wastes are not only the post-consumer products but also the scraps from the manufacturing unit, which is about 10% of the total PU production. Landfilling of PUs has serious environmental consequences, so it becomes the least favourable option. The decomposition of PUs in a garbage landfill in leakage water and by soil microorganisms exhibited a high level of resistance to biotic and abiotic conditions [9]. Moreover, Landfilling is forbidden in many European countries such as Netherlands, Denmark, Switzerland, Sweden and Germany [10]. Therefore, recycling and re-utilization of waste polymers have attracted much attention in recent times. To effectively recycle them, many researchers have focused on the transformation of plastic wastes into valuable carbon materials and their applications as adsorbent/ catalyst support in water treatment or chemical processes and as electrodes in energy storage devices.

This dissertation focuses on the effective recycling of difficult-to-recycle, post-industrial waste PU elastomer. A platform synthesis process was developed to convert the waste PU elastomers into carbon foams (CFs) with beneficial properties and explored the applications of CFs and their composites in energy storage and environmental remediation.

The overall objectives of this research are as follows:

- Synthesis of CFs using the waste PU elastomer as templates *via* two different activation routes and systematically investigating their physicochemical properties using different characterization techniques.
- Evaluation of the adsorption capacity of the synthesized CFs by conducting the equilibrium adsorption study using methylene blue (MB) dye as a model pollutant.
- Evaluation of the electrochemical performance of the CFs by analysing the parameters such as specific capacitance, energy density, power density and cycle stability.
- Synthesis and characterization of CF-supported bismuth oxychloride (BiOCl) composites and evaluated their photocatalytic performance *via* the degradation of the model pollutant MB dye.

2. Knowledge gap

- Although some studies reported the usage of PU flexible and rigid foams for the synthesis of CFs, the utilization of PU elastomer as a template for the synthesis of CFs is new. To the best of our knowledge, no works have ever reported the fabrication of CF from the PU elastomer and its application in any field. Hence, it is worth exploring the synthesis and characterization of CFs from waste PU elastomer and their applications in different areas including energy storage and environmental remediation.
- There is only limited research on the applicability of the two different activation approaches (namely direct activation route or one-step process and indirect activation route or two-step process) for the synthesis of activated carbons (ACs). However, the effect of the activation routes on the surface properties of the carbon materials and the reason for the difference in the surface characteristics have not been properly reported. Therefore, it is important to systematically investigate the effect of the two different activation routes on the porosity and surface functionalities of the carbon materials.
- Moreover, there has been no study on the preparation of CF-supported BiOCl photocatalysts for wastewater treatment. Hence the preparation and evaluation of the photocatalytic performance of the CF-BiOCl composite contribute to a new research direction. Moreover, it was reported that the use of a shape-controlling agent like Polyvinyl pyrrolidone (PVP) improved the properties of the composite by regulating the crystal structure of BiOBr (bismuth oxybromide) on carbon [11]. As a widely and efficiently used anionic surfactant, sodium dodecyl sulfate (SDS) has been used for the synthesis of novel morphologies of nanostructures [12]. Hence, the role of SDS in the formation of BiOCl nanostructure on the CFs is worth exploring.

3. Aim of thesis

The primary objective of this research work is to create an efficient method to recycle the waste PU elastomer. Hence, the current work aims to develop a new pathway to convert the post-industrial waste PU elastomers into porous CFs with beneficial properties and explore the applications of CFs and their composites in energy storage and wastewater treatment. The applicability of this type of waste polymer-derived CFs as adsorbent and electrode material and their composite in photocatalytic wastewater treatment is planned to investigate in line with multiple Sustainable Development Goals (SDGs) of the United Nations, e.g., Goals 6 (“Clean Water and Sanitation”), Goals 7 (“Affordable and Clean Energy”) and 12 (“Responsible Consumption and Production”) [13]. As such, the presented research simultaneously targets the objectives of circular economy, energy and environmental remediation.

In this work, I focus on answering the following questions:

1. Is it possible to prepare a porous CF by utilizing the waste PU elastomer as a template? What are their physicochemical properties?
2. What could be the effect of applying the two-different activation methods (one-step or direct activation and two-step or indirect activation routes) on the properties of the CFs?
3. Does the method of activation influence the adsorption capacity and the electrochemical properties of the CFs?
4. Can the as-prepared CF be used as a support material for the semiconductor BiOCl? How does it influence the structural and optical properties and also the photocatalytic performance of the BiOCl?
5. Does the usage of the CF support to the semiconductor photocatalyst necessarily decrease the band gap of the composite?

The current thesis consists of three parts:

- i. The first part is the preparation and characterization of CFs using the waste PU elastomers as sacrificial templates (and sucrose as a carbon source) *via* two different activation methods (One-step and two-step activation).
- ii. In the second part, the potential applications of CFs as electrodes in an electric double-layer capacitor (EDLC) and as adsorbents in pollutant removal will be explored. The electrochemical performances of the as-prepared CFs will be evaluated in an aqueous KOH electrolyte to explore potential utilization in EDLCs. Further, their adsorption capacity will be assessed by the equilibrium adsorption study of MB dye.
- iii. The third part is the synthesis and characterization of CF-supported BiOCl composites with and without the shape-tailoring agent SDS and the photocatalytic performance of the composites will be evaluated *via* the degradation of MB dye as a model pollutant.

4. Experimental section

4.1 Preparation of CFs

The CFs were prepared using PU elastomer as a sacrificial template and sucrose as a carbon source. The templates were immersed in an acidified sucrose solution followed by carbonization and activation. The sucrose precursor solution was prepared by adding 40 mL of 2.8% (v/v) dilute sulfuric acid to 100 g of sucrose in a glass beaker followed by heating to 80 °C under continuous stirring until complete dissolution. The foams were cut into 2.5 cm × 2.5 cm × 2.5 cm cubes and were immersed and kept in the precursor solution for 12 h. The excess solution was removed from the samples by squeezing in paper tissues. Thereafter, the impregnated samples were dried overnight at room temperature. Dried samples were cross-linked in a hot air oven at 110 °C for 10 h. After impregnation and drying, the mass of the residual sucrose precursor that remained in the elastomers was approximately twice that of the original mass of the raw foams. For activation, two different approaches were investigated: a one-step and a two-step activation process.

○ **Two-step activation**

In the two-step or indirect activation route, the first step was the carbonization of impregnated PU elastomers at 700 °C (EF700) or 900 °C (EF900) at a heating rate of 10 °C/min in an N₂ atmosphere (200 mL/min) with a dwell time of 60 min in a tube furnace (Carbolite® 1200 °C Split Tube furnace VST 12/900). In the second step, the carbonized samples were placed in a quartz crucible and activated inside a silica glass tube of the high-temperature tube furnace in a stream of CO₂ (200 mL/min). Then, the furnace was heated to a maximum temperature of 900 °C or 1000 °C, with a heating rate of 10 °C/min and the samples were left at this temperature for 100 minutes. The carbonized sample (EF900) activated in CO₂ at 1000 °C for 100 minutes is named 'EFAC2'.

○ **One-step activation**

In the one-step or direct activation route, the impregnated PU elastomer templates were directly activated using CO₂ gas without any prior carbonization. In this approach, the impregnated samples were activated in a stream of CO₂ with a flow rate of 200 mL/min and heated to 1000 °C at a heating rate of 10 °C/min with varying times of activation (30, 50, 80, 100 and 130 min) to identify the best activation time. The impregnated sample directly activated in CO₂ at 1000 °C for 100 minutes is named 'EFAC1'.

4.2 Preparation of CF-BiOCl composites

For the synthesis of CF-BiOCl composites, the high surface area EFAC1 was taken as a support material. Two types of composites were prepared with and without the addition of surfactant 'SDS'. Firstly, 2 mmol of Bi(NO₃)₃·5H₂O was dissolved in 40 mL of 0.15 M

nitric acid solution, denoted as 'Sol A'. 2 mmol of KCl was dissolved in 20 mL of deionized water, denoted as 'Sol B'. Then, SDS (0.4 g) was added to Sol A and stirred for 30 min to obtain a suspension. Subsequently, Sol B was added dropwise into the suspension and stirred for 30 min. Then, the CF (EFAC1 - 0.25 g) was added to the above mixture and shaken for 2 hours. The mixture was transferred to a Teflon-lined[®] autoclave and allowed to react at 160 °C for 12 h. After self-cooling to room temperature, the solid product was washed with deionized water and ethanol several times. Finally, the composite was obtained by drying at 70 °C overnight. The same procedure was followed for the synthesis of pristine BiOCl except for the addition of CFs.

5. Summary

The goal of this research was to create a basis and platform synthesis process of the CFs using the difficult-to-recycle waste PU elastomer that enables a wide range of applications including energy storage and wastewater treatment. Novel synthesis pathways enable novel applications *via* yielding complex, hierarchical material structures. The major observations of this research work are summarized here:

- In this work, we produced the activated CFs *via* two different activation pathways - one-step, direct activation in CO₂ and two-step activation in N₂ and CO₂. The yield of CF was higher when direct, one-step activation was used; furthermore, direct activation at 1000 °C in CO₂ for 100 minutes yielded CF with a high specific surface area (2127 m²/g). The obtained CFs have a hierarchical pore structure and exhibit a non-graphitized, turbostratic carbon nanostructure. The temperature and time of activation also played a significant role in obtaining CF with good surface properties. The one-step activation is simpler and appears more economical than the two-step activation.
- One of the main observations in our work was the difference in the specific surface area of the CFs achieved *via* the two methods of activation. The reason for this disparity is that in the two-step process, the tars formed during the first step of pyrolysis in N₂ created the secondary char (during cooling), which partially or completely filled the generated pores in the primary carbon matrix (char) and during the activation of this char, the CO₂ simultaneously remove the secondary char from the pores and also the carbons from the primary char resulting in lower specific surface area. On the other hand, in direct activation, the CO₂ reacted with the tars released from the impregnated foams, inhibiting the polymerization reaction and secondary char formation into the pores of the primary carbon matrix. Thus the CO₂ removed the carbon atoms only from the primary matrix and not the secondary char, producing high surface area CFs. However, the surface-bound functional group, especially the hydroxyl group and hence the hydrophilicity of CFs produced by the

two-step process was relatively higher, which was confirmed by the wettability test and XPS.

- Based on the high surface area, hierarchical pore configuration and surface functionalities of the CFs, we evaluated their adsorption capacity of MB and also the electrochemical performances in EDLCs. Equilibrium adsorption of methylene blue (MB) was best described by the Langmuir isotherm model with a maximum adsorption capacity of 592 mg/g and 437 mg/g for EFAC1 and EFAC2, respectively. We observed that the high surface area EFAC1 showed high MB adsorption capacity, while the highest affinity towards MB was observed in the case of EFAC2 due to its more surface-bound oxygen-containing functional groups, mainly the -OH group. Although the surface area and the pore structure of the CFs are crucial to accommodate the adsorbed MB, the presence of surface functional groups also played a vital role in increasing the adsorption capacity. Pertaining to the excellent adsorption capacity of MB, the as-prepared CFs have the potential as an adsorbent or catalyst support. Further surface modification might enable applications in wastewater treatment.
- Moreover, the EDLCs fabricated from the EFAC1 exhibited the highest gravimetric capacitance of 74.4 F/g at 0.1 A/g due to its high specific surface area. High packing density due to the presence of carbon spheres in the hierarchical structure offered excellent volumetric capacitance of 134.7 F/cm³ at 0.1 A/g. Besides, both CF-based EDLCs exhibited Coulombic efficiency close to 100% and showed stable cyclic performance for 5000 charge-discharge cycles with good capacitance retention of 97.7% at 3 A/g. On the contrary, EFAC2 exhibited low equivalent series resistance (1.05 Ω) and charge transfer resistance (0.23 Ω) due to the extensive presence of hydroxyl functional groups contributed to attaining high power (48.89 kW/kg). Hence, the hierarchical porous structure of EFAC1 does not necessarily enhance the ionic transport in the CFs as most reported. One major finding is that apart from the hierarchical porous structure, the surface-bound functional groups play a major role in determining the rate of diffusion of electrolyte ions into the CF electrodes. Therefore, the electrochemical performance of the CFs is not only controlled by the hierarchical pore structure and surface area but also the type and concentration of the oxygen-containing surface functional groups. Based on the preferred properties such as high specific surface area, hierarchical pore structure, surface functionalities, low metallic impurities, high conductivity and desirable capacitive behaviour, the CF prepared from waste PU elastomers have shown potential to be adopted as electrodes in EDLCs.
- Finally, we proposed the applicability of porous CF as a support material to the semiconductor BiOCl to improve its photocatalytic performance. EFAC1 was used to

synthesize the CF-BiOCl composites by a simple hydrothermal method in which the BiOCl micro flowers and plates were immobilized on the CF surface. The structure, morphology and optical properties of the composites were precisely characterized. The determination of the band gap from diffuse reflectance through double linear fit exhibit an increased band gap of the composites, which indicates that the addition of carbon does not necessarily decrease the band gap and shifts the absorption to the visible region for the UV-active BiOCl. The photocatalytic activity of the samples was evaluated by studying the degradation of methylene blue (MB) under UV-A irradiation. Even at a high MB concentration (0.5 mmol/L), excellent photocatalytic activity was observed with an overall removal efficiency of 99.0% in 100 minutes of irradiation. Kinetic studies were also carried out for the degradation of MB by pristine BiOCl and CF-BiOCl composites. The rate constants of the photodegradation were evaluated by fitting the kinetic data with a pseudo-first-order model and the rate constants of CF-BiOCl composites were higher than that of pristine BiOCl. Though a blue shift was seen for the composites in DRS, the lower crystallite size and higher specific surface area of the composites facilitated the complete removal of MB. It is found that the dominance of structural and surface properties together with hierarchical morphology has contributed to the photodegradation of MB rather than the optical property.

- Thus, our work contributes to the utilization of valuable waste PU elastomer-derived CFs and their composites in the energy storage device and wastewater treatment, which provides a strategy to reach the objective of circular economy, energy and environmental remediation.

6. Claims/New scientific results

The activated CFs were successfully synthesized from the waste PU elastomer following two different activation pathways – one-step (direct) and two-step (indirect) activation routes. The method of activation affects the textural and surface properties of the final product. The as-prepared CFs were tested for their applicability as electrodes in EDLCs, adsorbent and/or photocatalytic support material in wastewater treatment.

Claim 1. Effect of activation routes on the textural and surface properties of the CFs

I observed that there was a difference in the specific surface area, pore configuration and surface functionalities of the CFs synthesized *via* the two different activation routes. The difference in the surface area and porosity was observed in the nitrogen sorption test and the variation in their pore structure can be seen in the TEM images.

The reason behind the disparity in the surface area is explained as follows: in the two-step process, the tars formed during the first step of pyrolysis in N₂ created the secondary char (during cooling), which partially or completely filled the generated pores in the primary carbon matrix (char) and during the activation of this char, the CO₂

simultaneously remove the secondary char from the pores and also the carbons from the primary char resulting in lower specific surface area. On the other hand, in direct activation, the CO₂ reacted with the tars released from the impregnated foams, inhibiting the polymerization reaction and secondary char formation into the pores of the primary carbon matrix. Thus the CO₂ removed the carbon atoms only from the primary matrix and not the secondary char, producing high surface area CFs. However, the surface-bound oxygen-containing functional group, mainly the –OH group and hence the hydrophilicity of CFs produced by the two-step process was relatively higher, which was confirmed by the wettability test and XPS.

Claim 2: The pore size distribution of raw PU elastomer influences the formation of carbon spheres

Many micro- and nanosized carbon spheres were formed inside the porous structure of the CFs. From the CT pore and particle size distribution, the majority of the pores in the raw foams appeared in the range of 50 – 300 μm, whereas the particle sizes of carbon spheres were between 50 – 200 μm. With the evidence of the CT imaging, it appears likely that during pyrolysis or direct activation, the sucrose solution filled inside the pores of the elastomer template took the shape of the pore leading to the formation of many spherical carbon particles inside the porous architecture of the CFs.

Claim 3: Influence of hierarchical pore structure and surface functionalities on the adsorption capacity and electrochemical performances of the CFs

I established that not only the hierarchical porous structure but also the surface-bound functionalities of the CFs determine the adsorption capacity and electrochemical performances of the CFs. For instance, the high specific surface area EFAC1 showed a higher MB adsorption capacity of 592 mg/g than EFAC2 (437 mg/g), whilst the highest affinity towards MB was observed in the case of EFAC2 ($K_L = 0.92$ L/mg) due to its more surface-bound oxygen-containing functional groups, especially the –OH group. Although the surface area and the pore structure of the CFs are crucial to accommodate the adsorbed MB, the presence of surface functional groups also played a vital role in increasing the adsorption capacity.

Moreover, the EDLCs fabricated from the EFAC1 exhibited the highest gravimetric capacitance of 74.4 F/g at 0.1 A/g due to its high specific surface area. On the contrary, EFAC2 exhibited low equivalent series resistance (1.05 Ω) and charge transfer resistance (0.23 Ω) due to the extensive presence of oxygen-containing (mainly hydroxyl) functional groups contributed to attaining high power (48.89 kW/kg). Hence, the hierarchical porous structure of EFAC1 does not necessarily enhance the ionic transport in the CFs as most reported. Apart from the hierarchical porous structure, the surface-bound oxygen functional groups play a major role in determining the rate of diffusion of electrolyte ions into the CF electrodes. Therefore, the electrochemical performance of the CFs is not only

controlled by the hierarchical pore structure and surface area but also the type and concentration of the oxygen-containing surface functional groups.

Claim 4: Effect of carbon on the optical properties of the semiconductor catalyst

Most literature reported that the addition of carbon to the semiconductor photocatalyst reduces the band gap and exhibits a red shift to the visible region. The band gap energy was calculated using the Kubelka-Munk function $[(F(R)hv)^{\gamma}=A(hv-E_g)]$. While analysing the Tauc plot of $(F(R)hv)^{1/2}$ versus hv , the estimation of the band gap by the zero extrapolation of $(F(R)hv)^{1/2}$ is not valid (commonly used method in the literature), which overestimates the band gap value. Due to the strong light absorption of carbon in the visible region, the diffuse reflectance of the composites is lower than 100% due to which the onset of the Tauc representations is no longer close to zero and appears above zero in the $(F(R)hv)^{1/2}$ axis. As a result, a double linear fitting (extrapolation of the intersection of the dotted lines to zero of $(F(R)hv)^{1/2}$ axis) was applied for the Tauc plot. I established that the estimated band gap values by the double linear approach have shown an increase in band gap values for the composites compared to the pristine BiOCl, which was further confirmed with a blue shift of absorption maxima around 341 nm in the first derivative diffuse reflectance spectroscopy (DRS) curve ($dR/d\lambda$) of the composites. The particle size reduction of BiOCl was observed for the composites and we speculate that the lower crystallite sizes influence the adsorption edge of the BiOCl.

Claim 5: Applications of CFs in energy storage and environmental remediation

The specific capacitances (74.4 F/g and 63.0 F/g), energy densities (2.58 Wh/kg and 2.19 Wh/kg) and the maximum power (39.29 kW/kg and 48.89 kW/kg) of the CFs in this work are in the range of supercapacitor materials. Based on the preferred properties such as the high specific surface area, pore structure, surface functionalities, low metallic impurities, high conductivity and desirable capacitive behaviour, the CF prepared from waste PU elastomers have shown potential to be adopted as electrodes in EDLCs.

The maximum adsorption capacity of MB onto the CFs was estimated as 592 mg/g and 437 mg/g for EFAC1 and EFAC2, respectively. These values are comparable to, or higher than most earlier reported values. Based on the adsorption capacity of MB, the as-prepared EFAC1 can be categorized as an “excellent adsorbent”. Hence, the CFs, especially the EFAC1 can have the potential as adsorbent or catalyst support. Moreover, the EFCA1 was used as a support for the synthesis of the CF-BiOCl composites. The composites showed excellent photocatalytic activity and an overall MB removal efficiency of 99.0% in 100 minutes of UV irradiation, even at a high MB concentration of 0.5 mmol/L.

Thus, I established that the as-prepared CFs enable a wide range of applications including energy storage and environmental remediation.

7. Publications

Publications related to the thesis work

1. **M. Udayakumar**, N. Sharma, K. Hernadi, M. Finšgar, I. Kocserha, M. Leskó, I.M. Szilágyi, Z. Németh. Bismuth oxychloride microcrystals decorated carbon foams based on waste polyurethane elastomer for enhanced removal of methylene blue (Submitted to Separation and Purification Technology).
2. **M. Udayakumar**, P. Tóth, H. Wiinikka, J. S. Malhotra, B. Likozar, S. Gyergyek, A. K. Lesko, R. Thangaraj, Z. Németh. Hierarchical porous carbon foam electrodes fabricated from waste polyurethane elastomer template for electric double-layer capacitor. *Scientific Reports* 12, 11786 (2022).
IF - 4.996 (D1)
3. **M. Udayakumar**, B. El Mrabate, T. Koós, K. Szemmelveisz, F. Kristály, M. Leskó, Á. Filep, R. Géber, M. Schabikowski, P. Baumli, J. Lakatos, P. Tóth, Z. Németh. Synthesis of activated carbon foams with high specific surface area using polyurethane elastomer templates for effective removal of methylene blue. *Arabian Journal of Chemistry* 14(7), 103214 (2021).
IF - 6.212 (Q1)
4. **M. Udayakumar**, B. El Mrabate, T. Koós, K. Szemmelveisz, J. Lakatos, V. László, Z. Németh. Preparation and investigation of carbon foams from waste polyurethanes. *Circular Economy and Environmental Protection* 3(1), 5-15 (2019).

Other publications

1. T. Chauhan, **M. Udayakumar**, M. A. Shehab, F. Kristály, A. K. Lesko, M. Ek, D. Wahlqvist, P. Tóth, K. Hernadi, Z. Németh. Synthesis, characterization, and challenges faced during the preparation of zirconium pillared clays. *Arabian Journal of Chemistry* 15(4), 103706 (2022).
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2. **M. Udayakumar**, R. Zs. Boros, L. Farkas, A. Simon, T. Koos, M. Lesko, A.K. Lesko, K. Hernadi, Z. Németh. Composite Carbon Foams as an Alternative to the Conventional Biomass-Derived Activated Carbon in Catalytic Application. *Materials* 14, 4540 (2021).
IF - 3.748 (Q2)
3. Á. Prekob, **M. Udayakumar**, G. Karacs, F. Kristály, G. Muránszky, A.K. Leskó, Z. Németh, B. Viskolcz, L. Vanyorek. Development of Highly Efficient, Glassy Carbon Foam Supported, Palladium Catalysts for Hydrogenation of Nitrobenzene. *Nanomaterials* 11(5),1172 (2021).
IF - 5.719 (Q1)

4. **M. Udayakumar**, M. Kollár, F. Kristály, M. Leskó, T. Szabó, K. Marossy, I. Tasnádi, Z. Németh. Temperature and time dependence of the solvent-induced crystallization of poly(L-lactide). *Polymers* 2020, 12(5), 1065.
I.F - 4.329 (Q1)
5. B. El Mrabate, **M. Udayakumar**, E. Csiszár, F. Kristály, M. Leskó, L. Somlyai-Sipos, M. Schabikowski, Z. Németh. Development of bacterial cellulose-ZnO-MWCNT hybrid membranes: a study of structural and mechanical properties. *Royal Society Open Science* 2020, 7, 200592.
6. L. Vanyorek, Á. Prekob, E. Sikora, G. Muránszky, B. El Mrabate, **M. Udayakumar**, P. Pekker, B. Viskolcz, Z. Németh. Development of N-doped bamboo-shaped carbon nanotube/MgO nanocomposites. *Journal of Composite Materials* 54(6), 857-863 (2020).
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7. B. El Mrabate, **M. Udayakumar**, M. Schabikowski, Z. Németh. Comparative electron microscopy study of the ZnO/MWCNT nanocomposites prepared by different methods. *Circular Economy and Environmental Protection* 3(1), 16-24 (2019).
8. E. Bartfai, K. Nemeth, B. El Mrabate, **M. Udayakumar**, K. Hernadi, and Z. Nemeth. Synthesis, Characterization and Photocatalytic Efficiency of ZnO/MWCNT Nanocomposites Prepared Under Different Solvent Conditions. *Journal of Nanoscience and Nanotechnology* 19, 422-428 (2019).
I.F - 1.354 (Q4)

Conference presentations

1. **M. Udayakumar**, P. Tóth, H. Wiinikka, J. S. Malhotra, R. Vellacheri, Z. Németh. Preparation of porous activated carbon foam with a high specific surface area using a polyurethane elastomer template for the electric double-layer capacitor. *31st International Conference on Diamond and Carbon Materials (Elsevier) Online*, September 2021 (Oral).
2. **M. Udayakumar**, B. El Mrabate, T. Koós, K. Szemmelveisz, J. Lakatos, L. Vanyorek, Z. Németh. A comparative study of carbon foams prepared from waste polyurethanes under different pyrolysis conditions. *18th Austrian Chemistry Days*, Linz, Austria, September 2019 (Poster).
3. **M. Udayakumar**, B. El Mrabate, T. Koós, K. Szemmelveisz, J. Lakatos, L. Vanyorek, Z. Németh. Effective recycling of polyurethane wastes with enhanced CO₂ reduction. *9th Visegrad Symposium on Structural Systems Biology*, Szilvásvárad, Hungary, June 2019 (Poster).

4. **M. Udayakumar**, Z. Németh. Preparation and investigation of carbon foams from waste polyurethanes. *1st Science Unlimited Conference – Eotvos Symposium*, Miskolc, Hungary, May 2019 (Oral).

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