Materials Research Bulletin 191 (2025) 113550

Contents lists available at ScienceDirect

Materials Research Bulletin

journal homepage: www.elsevier.com/locate/matresbu

Research Papers

Card-bisphenol-based hybrid polybenzoxazine composites for high-*k* dielectrics: Activated vs non-activated *Phragmites karka* carbon

Janapriya Mathimani [a], Sasikumar Ramachandran [a,*], Poornesh Devaraj [a], Dharani Shri Ramachandran [b], Alagar Muthukaruppan [a,c,*]

[a] Polymer Engineering Laboratory, Department of Chemistry, PSG Institute of Technology and Applied Research, Neelambur, Coimbatore 641062, India
[b] Department of Chemistry, PSGR Krishnammal College for Women, Peelamedu, Coimbatore 641 004, India
[c] Centre for Advanced Materials, PSG College of Arts & Science, Coimbatore 641 014, India

ARTICLE INFO

Keywords:
Card-bisphenol
Phragmites karka
Activated carbon
Polybenzoazine
Bio-composites
Water contact angle
High-k dielectrics

ABSTRACT

Bio-based benzoxazine (CBPA-Bz) resin was synthesized using card-bisphenol derived from cardanol, and aniline with paraformaldehyde through Mannich condensation followed by thermal polymerization to obtain polybenzoxazine (CBPA-PBz). Free hydroxyl groups of the polybenzoxazine matrix developed on polymerization have been modified in the form of ester via esterification with dodecenyl succinic anhydride (DSA) at high temperature through in situ reaction. The non-activated bio-carbon (C_{na}) and acid-activated bio-carbon (C_{aa}) were derived from *Phragmites karka* (*p.karka*). Different weight percentages of bio-carbons reinforced hybrid CBPA-DSA-PBz-$C_{na/aa}$ polybenzoxazine composites were prepared, and studied their dielectric, thermal, and water-repellent properties. FTIR and ^{1}H NMR spectra were used to ascertain the molecular structure of the benzoxazine monomer and polymer composites. The hybrid CBPA-DSA-PBz and its composites exhibit higher values of water contact angle (WCA) between 141^o and 165^o infer their (super) hydrophobic behaviour compared to its pristine CBPA-PBz matrix (WCA = 140^o). The hydrophobic property of the developed polybenzoxazine (CBPA-DSA-PBz) and its composites (CBPA-DSA-PBz-$C_{na/aa}$1-10) could provide an authentic dielectric constant and dielectric loss values, because of preventing the effect of moisture on dielectric measurement. The CBPA-DSA-PBz-C_{na}10 and CBPA-DSA-PBz-C_{aa}10 hybrid composites show high values of dielectric constant, 6.97 and 7.55, respectively.

1. Introduction

Dielectric materials are insulators and are used in the electrical and electronic applications, they are essential for controlling the effect of electric fields. They are categorized into low-k and high-k dielectrics based on their values of dielectric constant (relative permittivity, ε_r), which discloses their ability to store electrical energy in an electric field. High-k dielectric materials have a high value of dielectric constant relative to silicon dioxide dielectric constant value of 3.94, and are used in semiconductor devices to increase speed, reduce power consumption, and improve performance of the devices. Therefore, they are essential in power electronics applications such as miniaturization of transistors, increase capacitance in capacitors, and reduce leakage currents, particularly in microelectronics [1–4].

The conventional polymer matrices limit their applications required for high-performance of electronic devices [5,6]. To overcome this drawback, Polybenzoxazines (PBzs) based composites possessing high-k dielectrics can be a choice, as they generally exhibit greater electrical and thermal properties than those of conventional polymers [7,8]. These consequences were replaced with PBzs due to their exceptional dimensional stability, high thermal stability, good flame-retardant behaviour, low-moisture absorption, excellent adhesive strength, catalyst-free polymerization, lightweight, good mechanical properties, high glass transition temperature (Tg), low surface free energy and good electrical properties. Additionally, PBzs offer smart macromolecular design flexibility, near-zero volumetric expansion, high char yield, and rapid improvement in physical and mechanical properties at low conversion. These advantages make PBzs an appealing alternative to traditional thermosetting resins such as phenolic, polyimide, epoxy, and bismaleimides [9–11].

The use of natural phenolic and polyphenolic compounds, including cardanol, vanillin, eugenol, urushiol, lignin, gallic acid, and coumarin,

* Corresponding authors.
E-mail addresses: rskmsc@gmail.com (S. Ramachandran), muthukaruppanalagar@gmail.com (A. Muthukaruppan).

https://doi.org/10.1016/j.materresbull.2025.113550
Received 31 January 2025; Received in revised form 2 May 2025; Accepted 10 May 2025
Available online 13 May 2025

500 °C to yield 12 % char at 850 °C. Whereas, the hybrid CBPA-DSA-PBz exhibits 29 % weight loss in the first degradation between 230 °C and 370 °C which might be due to the cleavage of ester linkages including the long aliphatic side chain of the cardanol unit, following the decomposition of polybenzoxazine networks occurred between 390 °C and 500 °C and 8 % char yield was obtained at 850 °C. Similar trend was observed in the case of bio-carbon reinforced CBPA-DSA-PBz-$C_{na/aa}$1-10 hybrid composites (Fig. 11), however, the char yield was increased up to 25 wt. % (CBPA-DSA-PBz-C_{na}10) with increasing the C_{na} content from 1 wt. % to 10 wt. % and the results obtained are presented in Table 2. The increased char yield considerably varied between C_{na} and C_{aa} reinforced polybenzoxazine composites, the activated carbon reinforced hybrid CBPA-DSA-PBz-C_{aa}10 composites exhibit 19 % char yield at 850 °C. This might be due to the presence of hydroxyl, carboxyl and carbonyl functional groups may interact with the polymer matrix and leads to degrade along with them, which influences the thermal decomposition and contributes to lower char yield at 850 °C.

4.7. *Water contact angle of the polybenzoxazine composites*

The water repellent/attraction behaviours of the materials could affect the dielectric properties of that materials because of the dielectric constant of water is about 80 at room temperature. Hence, it is desirable to study the water contact angle of the developed polybenzoxazine composites. As shown in Fig. 12, the hybrid CBPA-DSA-PBz (158^{o}) exhibits the higher value of water contact angle namely super hydrophobic when compared to that of neat CBPA-PBz (140^{o}) which infers the presence of additional long aliphatic chain in the cross-linker and the formation of ester linkages significantly influenced to enhance the value of water contact angle. Further, the C_{na} reinforced hybrid CBPA-DSA-PBz-C_{na}1-10 composites exhibit higher water contact angle in the ranges of 158-165^{o} which infers their super hydrophobic property. Whereas, the C_{aa} reinforced hybrid CBPA-DSA-PBz-C_{aa}1-10 composites displays the decreasing trend of the value of water contact angle with increasing percentage of C_{aa} which might be due to the presence of polar functional groups, intermolecular hydrogen bonding and modifying the surface free energy of the composites [68].

5. Conclusion

Utilisation of agricultural waste like cardanol derived from cashew nut shell liquid, and *p. karka* plant-based carbon for the development of polymer composites is an effective approach to obtain bio-based dielectrics. In the present work, a sustainable bio-based polybenzoxazine composites (CBPA-DSA-PBz-$C_{na/aa}$1-10) were developed as high-*k* dielectrics using card-bisphenol-based benzoxazine (CBPA-Bz), an anhydride (DSA), and non-activated (C_{na})/acid-activated (C_{aa}) bio-carbon. The neat CBPA-PBz matrix inherently exhibits the higher value of dielectric constant of 5.55 with hydrophobic nature, while the hybrid polybenzoxazine (CBPA-DSA-PBz) shows the lower value of dielectric constant (3.39) with super-hydrophobic behaviour. Further, the non-activated (C_{na}) or activated biocarbon (C_{aa}) reinforced hybrid polybenzoxazine composites exhibit an increased value of dielectric constant with increasing weight percentages of bio-carbon. The influential effect of acid-activated bio-carbon could increase the value of dielectric constant ($k = 7.55$) of the hybrid CBPA-DSA-PBz-C_{aa}10 when compared to that of non-activated bio-carbon reinforced hybrid CBPA-DSA-PBz-C_{na}10 composite ($k = 6.97$). This might be due to the oxidative products of polar functional groups, such as hydroxyl, carbonyl, and carboxylic acid present in the acid-activated carbon. Further, the developed polybenzoxazine composites remain thermally stable up to about 230 °C. After that, the composites underwent a two-step thermal degradation due to the decomposition of ester-linkages and long aliphatic side chain, following the polybenzoxazine networks. The present work provides an avenue for the development of bio-based high-k dielectrics and can create an impact in the miniaturization and advancement of the modern electronics devices.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

CRediT authorship contribution statement

Janapriya Mathimani: Writing – original draft, Data curation. **Sasikumar Ramachandran:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Poornesh Devaraj:** Data curation. **Dharani Shri Ramachandran:** Formal analysis, Data curation. **Alagar Muthukaruppan:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Acknowledgment

The authors thank the PSG Management, Secretary, and Principal, PSG Institute of Technology and Applied Research, Neelambur, Coimbatore, India, for their moral and financial support.

Data availability

Data will be made available on request.

References

[1] D. Shamiryan, T. Abell, F. Iacopi, K. Maex, Low-k, (n.d.).
[2] W. Volksen, R.D. Miller, G. Dubois, Low dielectric constant materials, Chem. Rev. 110 (2010) 56–110.
[3] A.G. Webb, Dielectric materials in magnetic resonance, Concepts Magn. Reson. A 38 (2011) 148–184.
[4] K. Yim, Y. Yong, J. Lee, K. Lee, H.-H. Nahm, J. Yoo, C. Lee, C. Seong Hwang, S. Han, Novel high-κ dielectrics for next-generation electronic devices screened by automated ab initio calculations, NPG Asia Mater. 7 (2015) e190–e190.
[5] M. Chen, H. Che, S. Yue, Exploring surface preparation for cold spraying on polymers, Surf. Coat. Technol. 450 (2022) 128993.
[6] B. Karahan, I. Ozdemir, T. Grund, N. Hanisch, T. Lampke, Advancements in cold spraying for polymer matrix composites: enhanced LSP and EMI shielding performance—Review and future directions, J. Mater. Sci. Mater. Eng. 20 (2025) 13.
[7] H. Manuspiya, H. Ishida, Polybenzoxazine-based composites for increased dielectric constant. Handb. Benzoxazine Resins, Elsevier, 2011, pp. 621–639.
[8] Z. Fan, B. Li, D. Ren, M. Xu, Recent progress of low dielectric and high-performance polybenzoxazine-based composites, Polym 15 (2023) 3933.
[9] M.G. Mohamed, S.-W. Kuo, Crown ether-functionalized polybenzoxazine for metal ion adsorption, Macromolecules 53 (2020) 2420–2429.
[10] K. Zhang, Y. Liu, H. Ishida, Polymerization of an AB-type benzoxazine monomer toward different polybenzoxazine networks: when diels–alder reaction meets benzoxazine chemistry in a single-component resin, Macromolecules 52 (2019) 7386–7395.
[11] M.G. Mohamed, S.W. Kuo, Functional silica and carbon nanocomposites based on polybenzoxazines, Macromol. Chem. Phys. 220 (2019) 1800306.
[12] J.R. Oliveira, L.R.V. Kotzebue, S.E. Mazzetto, D. Lomonaco, Towards bio-based high-performance polybenzoxazines: agro-wastes as starting materials for BPA-free thermosets via efficient microwave-assisted synthesis, Eur. Polym. J. 116 (2019) 534–544.

[13] P. Sharma, P. Dutta, L. Nebhani, Sustainable approach towards enhancing thermal stability of bio-based polybenzoxazines, Polym 184 (2019) 121905.
[14] H. Xu, Z. Lu, G. Zhang, Synthesis and properties of thermosetting resin based on urushiol, Rsc Adv. 2 (2012) 2768–2772.
[15] P. Froimowicz, C.R. Arza, L. Han, H. Ishida, Smart, sustainable, and ecofriendly chemical design of fully bio-based thermally stable thermosets based on benzoxazine chemistry, ChemSusChem 9 (2016) 1921–1928.
[16] M. Arslan, Synthesis and characterization of novel bio-based benzoxazines from gallic acid with latent catalytic characteristics, React. Funct. Polym. 139 (2019) 9–16.
[17] S. Shukla, N. Yadav, B. Lochab, Cardanol-based benzoxazines and their applications. Adv. Emerg. Polybenzoxazine Sci. Technol., Elsevier, 2017, pp. 451–472.
[18] I. Hamerton, High-performance thermoset-thermoset polymer blends: a review of the chemistry of cyanate ester-bismaleimide blends, High Perform. Polym. 8 (1996) 83–95.
[19] R. Patel, R. Trivedi, M. Raj, L. Raj, A brief review of polymeric blends based on natural polymers and synthetic thermoplastics polymers, Chem. Pap 78 (2024) 665–697.
[20] S. Rimdusit, H. Ishida, Development of new class of electronic packaging materials based on ternary systems of benzoxazine, epoxy, and phenolic resins, Polym 41 (2000) 7941–7949.
[21] C.H. Lin, Y.S. Shih, M.W. Wang, C.Y. Tseng, T.C. Chen, H.C. Chang, T.Y. Juang, Pyridinyl-containing benzoxazine: unusual curing behaviors with epoxy resins, Polym 55 (2014) 1666–1673.
[22] S. Rimdusit, H. Ishida, Synergism and multiple mechanical relaxations observed in ternary systems based on benzoxazine, epoxy, and phenolic resins, J. Polym. Sci. B Polym. Phys. 38 (2000) 1687–1698.
[23] H. Ishida, D.J. Allen, Mechanical characterization of copolymers based on benzoxazine and epoxy, Polym 37 (1996) 4487–4495.
[24] W. Li, J. Chu, L. Heng, T. Wei, J. Gu, K. Xi, X. Jia, A novel thermal-resistant copolymer from polysiloxane-based polybenzoxazine precursor and ferrocene-based benzoxazine monomer, Polym 54 (2013) 4909–4922.
[25] T. Takeichi, T. Agag, R. Zeidam, Preparation and properties of polybenzoxazine/poly (imide-siloxane) alloys: In situ ring-opening polymerization of benzoxazine in the presence of soluble poly (imide-siloxane) s, J. Polym. Sci. Polym. Chem. 39 (2001) 2633–2641.
[26] H. Ardhyananta, T. Kawauchi, H. Ismail, T. Takeichi, Effect of pendant group of polysiloxanes on the thermal and mechanical properties of polybenzoxazine hybrids, Polym 50 (2009) 5959–5969.
[27] T. Takeichi, Y. Guo, S. Rimdusit, Performance improvement of polybenzoxazine by alloying with polyimide: effect of preparation method on the properties, Polym 46 (2005) 4909–4916.
[28] T. Agag, T. Takeichi, Effect of hydroxyphenylmaleimide on the curing behaviour and thermomechanical properties of rubber-modified polybenzoxazine, High Perform. Polym. 13 (2001) S327–S342.
[29] S. Rimdusit, C. Jubsilp, Polymer from modification of polybenzoxazine with anhydride, Thail. Pat. (2007) 701003695.
[30] S. Rimdusit, B. Ramsiri, C. Jubsilp, I. Dueramae, Characterizations of polybenzoxazine modified with isomeric biphenyltetracarboxylic dianhydrides, EXPRESS Polym. Lett. 6 (2012).
[31] C. Jubsilp, T. Takeichi, S. Rimdusit, Property enhancement of polybenzoxazine modified with dianhydride, Polym. Degrad. Stab. 96 (2011) 1047–1053.
[32] C. Jubsilp, B. Ramsiri, S. Rimdusit, Effects of aromatic carboxylic dianhydrides on thermomechanical properties of polybenzoxazine-dianhydride copolymers, Polym. Eng. Sci 52 (2012) 1640–1648.
[33] S. Tiptipakorn, N. Keungputpong, S. Phothiphiphit, S. Rimdusit, Effects of polycaprolactone molecular weights on thermal and mechanical properties of polybenzoxazine, J. Appl. Polym. Sci. 132 (2015).
[34] Y. Xia, P. Yang, R. Zhu, C. Zhang, Y. Gu, Blends of 4, 4′-diaminodiphenyl methane-based benzoxazine and polysulfone: morphologies and properties, J. Polym. Res. 21 (2014) 1–8.
[35] C. Gaina, O. Ursache, V. Gaina, C.D. Varganici, Poly (urethane-benzoxazine) s, J. Polym. Res. 21 (2014) 1–11.
[36] C.G. Caldwell, O.B. Wurzburg, Polysaccharide derivatives of substituted dicarboxylic acids, (1953).
[37] W.R. Lockwood, L.L. Langston Jr, A reliable and easily sectioned epoxy embedding medium, Anat. Rec. 150 (1964) 129–139.
[38] F. Fu, M. Huang, W. Zhang, Y. Zhao, X. Liu, Thermally assisted self-healing behavior of anhydride modified polybenzoxazines based on transesterification, Sci. Rep. 8 (2018) 10325.
[39] I. Dueramae, C. Jubsilp, T. Takeichi, S. Rimdusit, High thermal and mechanical properties enhancement obtained in highly filled polybenzoxazine nanocomposites with fumed silica, Compos. B Eng. 56 (2014) 197–206.
[40] J. Kajohnchaiyagual, C. Jubsilp, I. Dueramae, S. Rimdusit, Thermal and mechanical properties enhancement obtained in highly filled alumina-polybenzoxazine composites, Polym. Compos 35 (2014) 2269–2279.
[41] H.A. Ghouti, A. Zegaoui, M. Derradji, W. Cai, J. Wang, W. Liu, A.Q. Dayo, Multifunctional hybrid composites with enhanced mechanical and thermal properties based on polybenzoxazine and chopped kevlar/carbon hybrid fibers, Polym 10 (2018) 1308.
[42] Y.-J. Hu, Y. Wang, Y.-H. Huang, J. Bian, M.-F. Li, F. Peng, R.-C. Sun, Benzoxazine enhanced amino cellulose-based composite films: preparation, proposed mechanism, and improved performance, Carbohydr. Polym. 222 (2019) 115008.
[43] T. Periyasamy, S.P. Asrafali, C.J. Raorane, V. Raj, D. Shastri, S.-C. Kim, Sustainable Chitosan/polybenzoxazine films: synergistically improved thermal, mechanical, and antimicrobial properties, Polym 15 (2023) 1021.
[44] S.P. Asrafali, T. Periyasamy, C.J. Raorane, R. Vanaraj, V. Raj, S.-C. Kim, Development of hybrid Titania/Polybenzoxazine composite for enhance thermomechanical, flame retardancy and dielectric properties, Sustainability 15 (2023) 1639.
[45] P. Madesh, S. Ramachandran, S. Appasamy, B. Krishnasamy, K. Muthu, A. Muthukaruppan, Valorization of agricultural waste to polybenzoxazine-carbon composites: studies on microstructure, thermal and dielectric properties, Eur. Polym. J. 197 (2023) 112355.
[46] M. Yuan, X. Lu, X. Ma, H. Lin, A. Lu, L. Shao, Z. Xin, Polybenzoxazine/organosilicon composites with low dielectric constant and dielectric loss, Chin. J. Chem. Eng. 64 (2023) 241–249, https://doi.org/10.1016/j.cjche.2023.06.024.
[47] K. Mohamed Mydeen, B. Krishnasamy, H. Arumugam, A. Muthukaruppan, Eco-friendly bio-based polybenzoxazine composites derived from sustainable thymol: A versatile approach and multifaceted study for enhanced applications, J. Polym. Sci. 62 (2024) 3959–3978.
[48] M. Aboughaly, A. Babaei-Ghazvini, P. Dhar, R. Patel, B. Acharya, Enhancing the potential of polymer composites using biochar as a filler: a review, Polym 15 (2023) 3981.
[49] V. Nagarajan, A.K. Mohanty, M. Misra, Biocomposites with size-fractionated biocarbon: influence of the microstructure on macroscopic properties, ACS Omega 1 (2016) 636–647.
[50] T.A.T. Yasim-Anuar, L.N. Yee-Foong, A.A. Lawal, M.A.A. Farid, M.Z.M. Yusuf, M. A. Hassan, H. Ariffin, Emerging application of biochar as a renewable and superior filler in polymer composites, RSC Adv 12 (2022) 13938–13949.
[51] A.A.K. Gorar, G. Zhiyi, W. Zhicheng, A. Daham, J. Wang, W.-B. Liu, Sustainable biocarbon derived from walnut shells and its composites with mono-functional bio-benzoxazine for advanced applications, Polym. Bull. (2025) 1–21.
[52] V. Selvaraj, T.R. Raghavarshini, M. Alagar, Design and development of bio-carbon reinforced hetero structured biophenolics polybenzoxazine-epoxy hybrid composites for high performance applications, J. Polym. Res. 28 (2021) 174.
[53] V. Selvaraj, T.R. Raghavarshini, Development of high-performance hybrid sustainable bio-composites from biobased carbon reinforcement and cardanol-benzoxazine matrix, Polym. Bull. 78 (2021) 4129–4148.
[54] P. Madesh, B. Krishnasamy, H. Arumugam, A. Muthukaruppan, Bio-based benzoxazine composites derived from magnolol: promising solution for sustainable alternatives for dielectric and superhydrophobic applications, Polym. Compos 45 (2024) 7137–7149.
[55] Kmk. Mydeen, Hm. BArumugam, A. KSMuthukaruppan, Sustainable strategies for fully biobased polybenzoxazine composites from trifunctional thymol and biocarbons: advancements in high-dielectric and antibacterial corrosion implementations, ACS Sustain. Chem. Eng. 12 (2024).
[56] S.P. Viswanthan, S.P. Neelamury, S. Parakkuzhiyil, G.V. Njazhakunnathu, A. Sebastian, B. Padmakumar, T.P. Ambatt, Removal efficiency of methylene blue from aqueous medium using biochar derived from Phragmites karka, a highly invasive wetland weed, Biomass Convers. Biorefinery (2020) 1–17.
[57] H. Zhang, L. Xu, G. Liu, Synthesis of benzoxazine-based n-doped mesoporous carbons as high-performance electrode materials, Appl. Sci. 10 (2020) 422.
[58] T. Pang, M. Zeng, Z. Feng, J. Chen, Y. Huang, Q. Xu, A facile method for the preparation of furfurylamine based benzoxazine resin with high-frequency low dielectric constants and ultra-low dielectric losses, J. Mater. Sci. Mater. Electron. 30 (2019) 8358–8370.
[59] A. Trejo-Machin, L. Puchot, P. Verge, A cardanol-based polybenzoxazine vitrimer: recycling, reshaping and reversible adhesion, Polym. Chem. 11 (2020) 7026–7034.
[60] M. Thommes, K. Kaneko, A.V Neimark, J.P. Olivier, F. Rodriguez-Reinoso, J. Rouquerol, K.S.W. Sing, Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report), Pure Appl. Chem. 87 (2015) 1051–1069.
[61] H. Arumugam, S. Krishnan, M. Chavali, A. Muthukaruppan, Cardanol based benzoxazine blends and bio-silica reinforced composites: thermal and dielectric properties, New J. Chem. 42 (2018) 4067–4080.
[62] S. Kurinchyselvan, A. Chandramohan, A. Hariharan, P. Gomathipriya, M. Alagar, Cardanol-based benzoxazine-terminated graphene oxide-reinforced fluorinated benzoxazine hybrid composites for low K applications, Compos. Interfaces 27 (2020) 737–751.
[63] K. Siraimeettan, H. Arumugam, C. Ayyavu, G. Ponnaiah, A. Muthukaruppan, Mechanical, thermal and dielectric studies of reduced graphene oxide reinforced cardanol based polybenzoxazine/epoxy nanocomposites, Compos. Interfaces 28 (2021) 461–476.
[64] V. Selvaraj, K.P. Jayanthi, T. Lakshmikandhan, M. Alagar, Development of a polybenzoxazine/TSBA-15 composite from the renewable resource cardanol for low-k applications, RSC Adv. 5 (2015) 48898–48907.
[65] H. Manuspiya, P. Laoratanakul, H. Ishida, Dielectric properties enhancement in polybenzoxazine composite at multi-frequency range, (2008).
[66] X. Hong, D.D.L. Chung, Exfoliated graphite with relative dielectric constant reaching 360, obtained by exfoliation of acid-intercalated graphite flakes without subsequent removal of the residual acidity, Carbon N. Y 91 (2015) 1–10.
[67] H. Demiral, İ. Demiral, Surface properties of activated carbon prepared from wastes, Surf. Interface Anal. Int. J. Devoted Dev. Appl. Tech. Anal. Surf. Interfaces Thin Film 40 (2008) 612–615.
[68] G.S. Prihandana, S.S. Maulana, R.S. Soedirdjo, V. Tanujaya, D.M.A. Pramesti, T. Sriani, M.F. Jamaludin, F. Yusof, M. Mahardika, Preparation and characterization of polyethersulfone/activated carbon composite membranes for water filtration, Membr 13 (2023) 906.