ORIENTAL JOURNAL OF CHEMISTRY
An International Open Access, Peer Reviewed Research Journal
www.orientjchem.org

ISSN: 0970-020 X
CODEN: OJCHEG
2024, Vol. 40, No.(2): Pg. 520-527

Harnessing the Potential of Coconut Shell Activated Carbon and Nitrogen-Doped Activated Carbon-Catalysts for Sustainable Power Generation (A-Review)

SAKTHIVEL R[1], MOHAMED ARFAYEEN R[2]*, ARUNA R[3], TABASSUM FATHIMA G[4], RIZWANA R[5] and ABINAYA S[2]

[1,2]Department of Electronics, PSG College of Arts and Science, Coimbatore-641 014, Tamil Nadu, India.
[3]Department of Biochemistry, SRM Arts and Science College, Kattankulathur-603 203, Tamil Nadu, India.
[4]Department of Mathematics, Gojan School of Business and Technology 80 Feet Road, Edapalayam, Redhills, Chennai, Tamil Nadu 600052, India.
[5]Department of Physics, B S Abdur Rahman Cresent Institute of Science and Technology, Vandalur, Chengalpattu dist, Tamil Nadu 600048, India.
*Corresponding author E-mail: arfu16elec@gmail.com

http://dx.doi.org/10.13005/ojc/400226

(Received: February 15, 2024; Accepted: April 19, 2024)

ABSTRACT

The rising demand for sustainable energy solutions has spurred intensive exploration into novel materials for energy storage and conversion. This review provides a comprehensive analysis of two synergistic materials, Coconut Shell Activated Carbon and Coconut Shell Nitrogen-Doped Activated Carbon, illustrating their potential in advancing power generation, energy storage, and environmental remediation. CSAC emerges as a versatile material renowned for its high surface area, porosity, and conductivity. Its application in fuel cell batteries showcases enhanced electrode performance and overall fuel cell efficiency. Additionally, CSAC displays promising characteristics in Lithium-ion batteries and supercapacitors, positively impacting energy density, power density, and cycling stability. Tailoring CSAC through synthesis and modification techniques addresses challenges related to cost and scalability, aligning seamlessly with sustainable practices. Environmental assessments underscore its eco-friendly nature, aligning with green energy initiatives. Future directions emphasize optimization strategies and innovative applications, highlighting CSAC's potential in advancing sustainable power generation technologies. On the other hand, CS-NAC, a nitrogen-doped variant derived from coconut shells, demonstrates remarkable performance in energy storage applications. Enhanced through nitrogen doping, it exhibits superior capacitance, prolonged cycle life, and improved charge-discharge kinetics, making it invaluable in cutting-edge energy storage systems. Its versatility extends to catalytic applications, especially in oxygen reduction reactions and environmental remediation, showcasing efficiency in adsorbing pollutants and heavy metals. Despite challenges in synthesis and scalability, CS-NAC's eco-friendly nature aligns with global initiatives for clean energy technologies. Future research directions focus on synthesis optimization, fundamental mechanism understanding, and innovative applications, positioning CS-NAC as a sustainable material addressing contemporary challenges in energy storage and environmental remediation. This combined potential underscores the pivotal role of these materials in shaping the future of energy science and environmental engineering.

Keywords: Activated carbon, Coconut shell, Nitrogen doping, X-ray Photoelectron Spectroscopy, Fourier Transform Infrared Spectroscopy, Brunauer-Emmett-Teller and Energy Storage Applications.

INTRODUCTION

Generating power is the backbone of modern civilization, fueling our homes, industries, and transportation. Traditionally, this electricity has been generated from fossil fuels like coal, oil, and natural gas. However, the depletion of these resources and their detrimental environmental impact necessitate a shift towards efficient and sustainable methods of power generation.

This is where Coconut Shell Activated Carbon emerges as a promising candidate. CSAC is a versatile material derived from coconut shells, a readily available and renewable resource[1]. This sustainable material possesses a high surface area, excellent adsorption capacity, and good electrical conductivity, making it ideal for a multitude of power generation applications.

Activated carbon materials have gained immense popularity in various fields, especially in energy storage and environmental remediation[2]. Their high porosity and surface area allow for efficient adsorption of pollutants and storage of energy[3]. The introduction of nitrogen atoms through doping further enhances these properties, leading to improved adsorption capacity, electrical conductivity, and catalytic activity[4].

Coconut shells are particularly well-suited for the production of activated carbon due to their high carbon content and cellular structure. This natural precursor offers a cost-effective and environmentally friendly alternative to traditional activated carbon sources.

By combining the inherent properties of activated carbon with the benefits of nitrogen doping, coconut shell-derived nitrogen-doped activated carbon (CS-NAC) emerges as a highly promising material for advancing the field of power generation. Its potential applications include; CS-NAC's high surface area and enhanced conductivity facilitate efficient electrochemical reactions for electricity generation such as fuel cells, the excellent energy storage capabilities of CS-NAC make it ideal for developing high-performance supercapacitors, CS-NAC's ability to capture impurities from various fuels can contribute to cleaner and more efficient energy production as adsorbent, CS-NAC's electrocatalytic activity can be harnessed for various energy conversion processes, like hydrogen production through water splitting.

CSAC has emerged as a versatile and sustainable material with diverse applications, particularly in power generation and environmental remediation[5]. Derived from the abundant and renewable resource of coconut shells, CSAC possesses unique properties that set it apart as an exceptional material for various technological applications.

Coconut shells are a natural byproduct of the coconut industry, and their conversion into activated carbon involves a process of thermal decomposition and activation[6]. This process creates a highly porous structure, characterized by an extensive network of pores and a large surface area. The resulting CSAC exhibits unique properties that make it highly suitable for a range of applications, including power generation.

One of the standout features of CSAC is its high surface area[7]. The porous structure of CSAC provides an extensive and accessible surface area, facilitating effective adsorption and reaction processes. This attribute is particularly beneficial in power generation applications[8], where the efficiency of energy storage and conversion devices depends on the material's ability to interact with various ions and molecules.

The exceptional porosity of CSAC further contributes to its applicability in power generation[9]. The presence of micropores, mesopores, and macropores[10] enhances the material's ability to adsorb and store ions, facilitating processes such as charge storage in supercapacitors[11] or ion transfer in fuel cells. This structural characteristic is crucial for improving the performance of energy storage devices by providing ample sites for electrochemical reactions.

In addition to its surface area and porosity, CSAC exhibits excellent conductivity[12], making it a preferred material for applications in power generation. The conductivity of CSAC is attributed to the graphitic structure[13] developed during the activation process, allowing efficient electron transfer in electrochemical devices. This conductivity is particularly advantageous in fuel cell applications[14], where electron transport is a critical factor in overall performance.

The environmentally friendly nature of CSAC further contributes to its appeal in power generation technologies. As a renewable resource, coconut shells offer a sustainable precursor for activated carbon, aligning with global initiatives for green and clean energy solutions. The use of CSAC not only provides a functional material for power generation but also supports the principles of environmental sustainability[15].

In summary, coconut shell activated carbon stands out as a promising material for power generation due to its unique properties. The high surface area, porosity, and conductivity of CSAC make it well-suited for applications in fuel cells, supercapacitors, and other energy storage devices. As the world continues to seek sustainable solutions for power generation, the versatile and eco-friendly nature of CSAC positions it as a key player in advancing the field of energy science and engineering.

Synthesis and modification of CSAC and CS-NAC

The synthesis and modification of CSAC and CS-NAC play a pivotal role in tailoring their properties for optimal performance in power generation applications. Various methods are employed to enhance their surface characteristics, porosity, and conductivity, contributing to their effectiveness in applications such as fuel cells, supercapacitors, and batteries.

Synthesis of CSAC

The synthesis of CSAC typically begins with the carbonization of coconut shells. This process involves heating the shells in an inert atmosphere, such as nitrogen or argon, to remove volatile components and convert the material into charcoal. Activation is a crucial step that imparts the high porosity characteristic of activated carbon. Two main methods are commonly used; physical activation involves exposing the carbonized material to high temperatures and activating gases, while chemical activation involves treatment with activating agents such as potassium hydroxide (KOH) or phosphoric acid (H_3PO_4). This creates pores and increases the material's surface area, optimizing its adsorption and energy storage capabilities.

Modification Techniques for CSAC

CSAC can be chemically modified by introducing functional groups onto its surface. This is achieved through reactions with acids, bases, or other chemical agents. These functional groups can enhance the material's interaction with specific ions or molecules, making it more effective in power generation applications. The addition of metal oxides, such as manganese oxide (MnO_2) or iron oxide (Fe_2O_3), can enhance the electrochemical properties of CSAC. These metal oxides act as redox-active materials, contributing to the capacitive behavior of CSAC in supercapacitors and batteries.

Synthesis of Nitrogen-Doped Activated Carbon (NAC)

Nitrogen doping can be achieved during the carbonization step by introducing nitrogen-containing precursors, such as ammonia (NH_3) or urea[22] to the coconut shell precursor. The presence of nitrogen functionalities, including pyridinic, pyrrolic, or graphitic nitrogen, enhances the electrochemical properties of the resulting NAC.

NAC can also be synthesized through chemical vapor deposition[16], where nitrogen-containing gases, such as ammonia, are introduced during the activation process. This allows precise control over the nitrogen content and configuration in the activated carbon structure.

Modification Techniques for Nitrogen-Doped Activated Carbon (NAC)

Similar to CSAC, NAC can undergo surface functionalization to introduce additional functional groups. This can be achieved through chemical treatments, enhancing the material's reactivity and adsorption capabilities. The type and concentration of nitrogen dopants in NAC can be tailored by adjusting the synthesis conditions. This fine-tuning of the nitrogen configuration influences the electrochemical performance of NAC in power generation applications.

In summary, the synthesis and modification of CSAC and NAC involve a combination of carbonization, activation, and post-treatment steps. These processes are carefully designed to optimize the materials for specific power generation applications, ensuring that they exhibit high surface area, tailored porosity, and enhanced conductivity. The choice of synthesis and modification methods depends on the desired properties and the targeted application, highlighting the versatility and tunability of these carbon materials in the field of energy storage and conversion.

Several studies have been conducted to evaluate the performance and efficiency of power generation systems incorporating CSAC[13]. These investigations span a range of applications, including fuel cells, supercapacitors, and batteries, showcasing the versatility of CSAC in diverse energy storage and conversion technologies.

Fuel cells

Studies examining the utilization of CSAC in fuel cells have consistently demonstrated positive outcomes. The high surface area and porosity of CSAC contribute to enhanced electrode performance, improving the overall efficiency of fuel cells. The porous structure of CSAC provides ample active sites for catalytic reactions, particularly in the oxygen reduction reaction (ORR) at the cathode.

Research findings indicate that CSAC effectively promotes the electrochemical processes within fuel cells, leading to increased power output and improved fuel cell efficiency. The sustainable nature of coconut shells as a precursor aligns with the growing emphasis on green and clean energy solutions. However, variations in CSAC synthesis methods and activation techniques across studies can influence specific performance metrics, highlighting the need for standardized protocols for a comprehensive comparison.

Supercapacitors

The use of CSAC in supercapacitors has been a subject of extensive investigation, with consistent observations of its positive impact on energy storage performance. CSAC's high surface area and conductivity contribute to increased energy density and power density in supercapacitors. The porous structure allows for efficient charge storage and rapid charge-discharge cycles.

Comparative studies across different research findings emphasize CSAC's ability to enhance the overall capacitance and cycling stability of supercapacitors. However, variations in precursor materials, activation methods, and electrode configurations can lead to differences in specific performance metrics. Despite these variations, the collective evidence supports CSAC as a valuable material for advancing supercapacitor technologies.

Batteries

The application of CSAC in batteries, particularly lithium-ion batteries (LIBs), has yielded promising results. CSAC's5 unique properties, such as its high surface area and porosity, contribute to improved ion storage and transport within the battery electrodes. Studies consistently show enhanced capacity, charge-discharge rates, and cycle life in batteries incorporating CSAC.

Comparative analyses of different research findings underscore the positive impact of CSAC on battery performance. However, variations in electrode configurations, electrolyte compositions, and testing conditions can influence specific outcomes. Standardization of testing protocols is crucial for a comprehensive comparison of CSAC's effectiveness in various battery systems.

Activated carbon derived from coconut shells has gained significant attention as a versatile and sustainable material, finding applications across various industries due to its unique properties and the eco-friendly nature of its precursor.

The production of activated carbon from coconut shells involves a multi-step process that begins with the collection of coconut shells, a byproduct of the coconut industry. After collection, the shells undergo a carbonization process[17], where they are heated in the absence of air to remove volatile compounds and convert the material into charcoal. The resulting charcoal is then activated through a controlled oxidation process, typically involving steam or chemical activation. This activation step creates a highly porous structure with an extensive internal surface area.

The unique properties of coconut shell-derived activated carbon make it well-suited for a diverse range of applications. One standout characteristic is its high surface area. The porous structure developed during activation results in a significantly large surface area, providing abundant sites for adsorption and chemical reactions. This property is particularly advantageous in applications such as water treatment[18], air purification[19], and gas separation[20], where efficient adsorption of contaminants is essential.

The microporous and mesoporous nature of coconut shell-derived activated carbon further enhances its adsorption capabilities[21]. The presence of different pore sizes accommodates a variety of molecules and ions, making it effective in selectively adsorbing specific contaminants. This property is exploited in industries such as wastewater treatment, where activated carbon is utilized to remove pollutants, organic compounds, and heavy metals from effluent streams[22].

The sustainability of coconut shell resources is a key factor contributing to the appeal of activated carbon derived from this precursor. Coconut trees are abundant in tropical regions, and the harvesting of coconuts for their meat and water generates a substantial amount of shells as waste. Utilizing these shells to produce activated carbon not only provides a valuable application for an otherwise discarded material but also aligns with the principles of circular economy and environmental conservation.

The renewable nature of coconut shell resources ensures a continuous and sustainable supply for activated carbon production. This stands in contrast to some other precursors, where concerns about deforestation and environmental impact may arise. The abundance and regenerative nature of coconut trees make coconut shells an environmentally friendly choice for activated carbon production, supporting the growing demand for sustainable solutions in various industries.

To sum up, activated carbon derived from coconut shells is a versatile and sustainable material with unique properties that make it suitable for a wide range of applications. The production process, involving carbonization and activation, creates a porous structure with high surface area and adsorption capabilities. The sustainable and renewable nature of coconut shell resources adds to the appeal of this activated carbon, making it an environmentally friendly choice for industries seeking effective and eco-conscious solutions for purification, filtration, and adsorption processes.

Nitrogen doping has become a prominent strategy to enhance the properties of activated carbon, offering avenues for tailoring its physicochemical characteristics for improved performance in various applications. This review focuses on nitrogen doping techniques applied specifically to coconut shell-derived activated carbon (CSAC) and explores the consequential impact on surface area, pore structure, and conductivity.

Several nitrogen doping techniques have been employed to modify activated carbon, and their applicability to coconut shell-derived carbon underscores the versatility of these methods. Among the widely used techniques are gas-phase processes like ammonia treatment, liquid-phase methods involving nitrogen-containing precursors, and solid-phase approaches utilizing nitrogen-rich compounds[23]. Each technique introduces nitrogen functionalities to the carbon matrix, influencing its properties in unique ways.

Nitrogen doping significantly impacts the surface area of activated carbon, a crucial factor influencing its adsorption capacity. The introduction of nitrogen functionalities creates additional active sites on the carbon surface, increasing the available surface area for interactions with adsorbates. This enhancement is particularly important for applications such as gas separation and pollutant removal, where increased surface area directly correlates with improved adsorption performance.

Pore structure, another critical aspect of activated carbon influencing its adsorption capacity, is also influenced by nitrogen doping. The incorporation of nitrogen functionalities can lead to the formation of new pores or modify existing ones. This alteration in pore structure affects the distribution and accessibility of pores, impacting the adsorption of different molecules based on size and polarity. Understanding these changes is vital for tailoring activated carbon to specific applications, such as controlling pore size for selective adsorption in gas storage or catalysis.

Conductivity is a key parameter in applications such as energy storage devices, where rapid charge/discharge rates are essential. Nitrogen doping plays a crucial role in enhancing the electrical conductivity of activated carbon. The introduction of nitrogen atoms into the carbon lattice creates additional charge carriers, improving the overall conductivity of the material. This enhancement is particularly beneficial in supercapacitors and batteries, where efficient electron transport is vital for achieving high-performance energy storage systems.

When focusing on coconut shell-derived activated carbon, the choice of nitrogen doping technique becomes critical. The unique precursor properties and activation processes of coconut shells may influence the effectiveness of certain doping methods. Tailoring the nitrogen doping technique to the specific characteristics of coconut shell-derived carbon ensures optimal modifications that align with desired applications.

In summary, nitrogen doping techniques offer a versatile means to enhance the physicochemical properties of activated carbon, particularly when derived from coconut shells. The impact on surface area, pore structure, and conductivity is pivotal for applications ranging from environmental remediation to energy storage. Tailoring nitrogen doping techniques to the characteristics of coconut shell-derived carbon provides a nuanced approach to optimizing the material for specific applications, offering a sustainable and effective solution in the realm of advanced materials science.

Characterization techniques play a pivotal role in understanding the structure and properties of nitrogen-doped activated carbon derived from coconut shells. This review explores key methods, including X-ray photoelectron spectroscopy, Fourier-transform infrared spectroscopy, and Brunauer–Emmett–Teller surface area analysis, to gain insights into the unique characteristics of nitrogen-doped activated carbon, specifically derived from coconut shells.

X-ray Photoelectron Spectroscopy

XPS is an invaluable technique for characterizing the elemental composition and chemical states of materials. In the context of nitrogen-doped activated carbon from coconut shells[24] (CS-NAC), XPS[25] provides critical information about the nitrogen functionalities incorporated during the doping process. It enables researchers to identify the types of nitrogen species, such as pyridinic or graphitic nitrogen[26] and quantify their relative concentrations. XPS is instrumental in elucidating the chemical environment of nitrogen atoms, offering insights into the structural modifications induced by nitrogen doping.

Fourier-Transform Infrared Spectroscopy

FTIR is a powerful analytical tool for investigating the functional groups present in a material. In the case of CS-NAC, FTIR[27] is employed to identify the nitrogen-containing functional groups introduced during the nitrogen-doping process. Amines, amides, and nitriles are among the common nitrogen functionalities identified through FTIR spectra. This information is crucial for understanding the surface chemistry of CS-NAC and its implications for adsorption, catalysis, and other applications. FTIR spectra provide a molecular-level understanding of the changes induced by nitrogen doping, aiding in the optimization of the doping process.

Brunauer–Emmett–Teller Surface Area Analysis

BET surface area analysis is essential for determining the specific surface area and porosity of CS-NAC. The porous structure of activated carbon is a key factor influencing its adsorption capacity. BET[28] analysis involves measuring the amount of gas adsorbed at different pressures, allowing the calculation of the material's surface area. For CS-NAC, this analysis provides crucial information about how nitrogen doping affects the porosity, pore size distribution, and overall surface area. Understanding these parameters is vital for tailoring CS-NAC to specific applications where surface area and porosity are critical factors.

Combining information from XPS, FTIR, and BET surface area analysis allows for a comprehensive characterization of CS-NAC. These techniques collectively help to understanding the nitrogen content, chemical environment, and surface properties of the material. The insights gained from this characterization process facilitate the optimization of CS-NAC for targeted applications, whether in energy storage, catalysis, or environmental remediation.

The characterization of nitrogen-doped activated carbon derived from coconut shells involves a multi-technique approach, with XPS, FTIR, and BET surface area analysis playing pivotal roles. This comprehensive characterization is crucial for harnessing the unique properties of CS-NAC and tailoring it for specific applications, contributing to the broader field of sustainable and efficient materials for diverse industrial and environmental purposes.

Power generation technologies

Power generation technologies have witnessed a paradigm shift with the integration of innovative materials, particularly coconut shell activated carbon (CSAC) and nitrogen-doped activated carbon (NAC). This review provides an overview of diverse power generation applications, specifically focusing on fuel cells, supercapacitors, and batteries, and discusses the unique advantages associated with the utilization of CSAC and NAC.

CONCLUSION

In conclusion, coconut shell-derived nitrogen-doped activated carbon represents a significant step towards achieving a sustainable and efficient future for power generation. Its versatility, coupled with its renewable nature and enhanced properties, makes it a material with immense potential to revolutionize the energy sector. Further research and development efforts focused on optimizing synthesis methods, tailoring material properties, and exploring innovative applications will undoubtedly unlock the full potential of CS-NAC and pave the way for a cleaner and more sustainable future. Thus the nitrogen doping of porous carbon material enhances the electrochemical performances of electrode material, thereby increases the energy storage behavior of supercapacitors.

ACKNOWLEDGMENT

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declared No conflicts of interest.

REFERENCE

1. Lee, C.L.; Chin, K.L.; H’ng, P.S.; Rashid, U.; Maminski, M.; Khoo, P.S., *Environmental Technology & Innovation.*, **2020**, *21*, 101309.
2. Rishika, C.; Vilya, K.; Mukul, P.;Arpan, K. N., *J. Mater. Chem. A.*, **2022**, *10*, 6965-7005.
3. Kamal, K.K., *Springer Series in Materials Science.*, **2020** (https://doi.org/10.1007/978-3-030-52359-6).
4. Podyacheva, O.Yu.; Ismagilova, Z.R., *Catalysis Today.*, **2015**, *249*, 12-22.
5. Anina, J.; Deepika, Y., *Environmental Technology & Innovation.*, **2021**, *24*, 102075.
6. Erwan, A.S.; Varadila, D.R.W.; Bellani, Y.W.; Rachmad, R.Y.; Nove, K.E., *Journal of Science and Technology.*, **2020**, *09*, 23-28.
7. André, L.C.; Osvaldo, P.J.; Alexandro, M.M.V.; Silva, A.P.; Xiaoxin, Z.; Tewodros, A.; Almeida, V.C., *Journal of Analytical and Applied Pyrolysis.*, **2013**, *101*, 53-60.
8. Noemi, A.; Jacquetta, L.; Roland, C., *Journal of Cleaner Production.*, **2016**, *125*, 68-77.
9. Sun, L.; Chungui, T.; Meitong, L.; Xiangying, M.; Wang,L.; Ruihong, W.; Yina, J.; Honggang, Fu., *Journal of Materials Chemistry A.*, **2013**, *1*, 6462-6470.
10. Wan Mohd, A.W.D.; Wan Shabuddin W.A., *Bioresource Technology.*, **2004**, *93*, 63–69.
11. Iqbaldin, M.N.M.; Khudzir, I.; Azlan, M.I.M.; Zaidi, A.G.; Surani, B.; Zubri, Z., *Journal of Tropical Forest Science.*, **2013**, *25*, 497-503.
12. Neethu, B.; Bhowmick, G.D.; Ghangrekar, M.M., *Biochemical Engineering Journal.*, **2019**, *148*, 170–177.
13. Keppetipola, N.M.; Maithri, D.; Pubudu, D.; Buddhika, K.; Marie, A.D.; David, T.; Laurent, S.; Céline, O.; Thierry, T.; Satoshi, U.; Kirthi, T.; Asoka, G.R.; Ludmila, C., *Royal Society of Chemistry.*, **2021**, *11*, 2854-2865.
14. Neethu, B.; Bhowmick, G.D.; Ghangrekar, M.M., *Biochemical Engineering Journal.*, **2019**, *148*, 170–177.
15. Glogic, E.; Kamali, A.K.; Keppetipola, N.M.; B.A.; Asoka, G. R.; Guido, S.; Thierry, T.; Ludmila, C., *American Chemical Society.*, **2022**, *10*(46), 15025–15034.
16. Seung, J.Y.; Kwanyong, P.; Moo, J.K.; Munkyu, J.; Bong, J.K.; Myung, S.O.; Jieung, B.; Hongkeun, P.; Goro, C.; Heung, K.; Junhwan, C.; Yunho, C.; Jihye, S.; Heeyeon, M.; Eunjung, L.; Sung,G.I., *Advanced Engineering Material.*, **2018**, *20*, 1700622.
17. Fatma, T.; Yasin, A.; Burcu, K.; Digdem,T.; Erdal, K.; Lima,E.C.; Nguyen, T. H., *Science of the Total Environment.*, **2020**, *726*, 137828.
18. Reza, M.S.; Cheong, S.Y.; Shammya, A.; Nikdalila, R.; Bakar, M.S.A.; Rahman, S.; Juntakan,T.; Azad, A.K., *Arab Journal of Basic and Applied Sciences.*, **2020**, *27*, 208–238.

19. Aditya, R.; Chetan, M.; Sarthak, J.; Naveen S., *J of Thermal Engineering.*, **2019**, *5*, 22-28.
20. Zhiyuan, Y.; Xiaoqian, J.; Hongbin, L.; Zhuoyue, M.; Hailong, N.; Yinyan, L.; Zhiping, C.; Jiang, L., *ACS Omega.*, **2021**, *6*, 19799–19810.
21. Sundaramurthy, J.; Akshay, J.; Mani, U.; Eldho, E.; Srinivasan, M.P.; Rajasekhar, B.; Vanchiappan, A.; Srinivasan, M., *Chemical Engineering Journal.*, **2017**, *316*, 506-513.
22. Mohan, D.; Singh, K. P.; Singh V. K., *Journal of Hazardous Materials.*, **2008**, *152,* 1045–1053.
23. Zhang, Y.; Shizhang, W.; Dongdong, F.; Jianmin, G.; Linhan, D.; Yijun, Z.; Shaozeng, S.; Yudong, H.;Yukun, Q., *Energy Fuels.*, **2022**, *36*(6), 2945–2970.
24. Liu, Q.; Ke, M.; Liu, F.; Yu, P.; Hu, H.; Li, C., *RSC Adv.*, **2017**, *7*, 22892.
25. Zhai, Y.; Xu, B.; Zhu, Y.; Qing, R.; Peng, C.; Wang, T.; Li, C.; Zeng, G., *Mater. Sci. Eng. C Mater. Biol. Appl.*, **2016**, *61*, 449-56.
26. Deng, C.; Xu, L.; Hu, K.; Chen, X.; Gao, R.; Zhang, L.; Wang, L.; Zhang, C., *Atmosphere.*, **2023**, *14*, 1510.
27. Rajasekaran, N.; Vinoba, M.; Al-Sheeha, H.; Rana, M.S., *Chemistry Select.*, **2021**, *6*, 9149-9156.
28. Borghei, M.; Laocharoen, N.; Poldsepp, E.; Johansson, L.; Campbell, J.; Kauppinen, E.; Tammeveski, K.; Rojas, O., *J. Appl. Catal. B: Environ.*, **2016**, *204*, 394-402.