JOURNAL OF MARITIME RESEARCH

Vol XXIII. No. II (2026) pp 484–490

**ISSN: 1697-4840, www.jmr.unican.es**

# Eco-Friendly Activated Carbon from Oman Seashells: A Step Toward Cleaner Marine Operations

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*ARTICLE INFO*

***Article history:***
Received 27 Jan 2026;
in revised form 16 Feb 2026;
accepted 21 Apr 2026.

***Keywords:***
activated carbon; eco-friendly; marine source; seashell; wastewater treatment.

*ABSTRACT*

This study explores the use of activated carbon derived from marine source seashells and date syrup for effective of micropollutant treatment (acetaminophen, Potassium chromate) aligning with environmental compliance and green shipping initiatives. The produced activated carbon (micro, meso and macro pore) exhibited a high surface area of 850 $m^2$/g and adsorption capacity of 150 mg/g for heavy metal chromium, demonstrating excellent pollutant removal efficiency. Batch adsorption tests revealed optimal performance at pH 6 with a contact time of 120 minutes and the maximum yield of 73.5% for Acetaminophen micro pollutant and 68.75% potassium chromate for HTL. The material showed strong reusability, maintaining 74% efficiency after five cycles. Integration of this sustainable adsorbent supports cleaner maritime operations by reducing toxic discharge into marine environments. Its local availability and cost-effectiveness enhance feasibility for widespread adoption in shipping wastewater management.



## 1. Introduction.

Effluent management is a critical process for protecting the common public health and safeguarding the aquatic and marine ecosystems. Due to industrialization and urban population expansion, effective solutions are necessary in most sectors, particularly sustainable water treatment solutions, as they have become essential in addressing global warming and unforeseen weather conditions. There are many treatment processes that take place, such as the sewage treatment process, wastewater treatment, and effluent treatment. The Activated Carbon (AC) has enhanced a foundation in novel wastewater management due to its remarkable capacity to adsorb a comprehensive scale of waste product (macro & micro), from carbon-based mixtures to heavy metallic element.

The metal industrial waste contains different forms of Chromium compounds, produced by electroplating industries, tanning industries and dying industries (Peña-Guzmán et al., 2019). Some of the specialized areas like ocean zones, the marine sewage treatment plants pay the combined process for treatment and integrating oxidative degradation and physical disinfections and sterilization to treat domestic wastewater from shipboard lavatories and bathrooms. Furthermore, onboard waste management contains nutrient rich wastewater, pathogen to disturb the marine ecosystem and it creates harsh conditions for the maritime environment and water pollution (Ying and Weber Jr, 1979, Weber Jr et al., 1987).

Activated Carbon (AC) is used in granular form, powdered form, and blocked activated carbon. The most efficient material for removing impurities and contaminants from aquatic areas. There are many benefits in everyday life, especially when uti-

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lized in organic chemicals, pharma, food and soft drinks industries, water treatment facilities, and home water filters. Most chemicals, such as chlorine, silt, volatile organic compounds (VOCs), and unpleasant tastes and odors, are eliminated in this way. The impurities recovery improves the water quality, depending on the pH balance and improving the taste and clarity. The Activated material is environmentally friendly and safe to use, so it does not produce unsafe by-products.

The Activated Carbon (AC) is mostly manufactured from coconut shell, coal and wood and other materials. It creates a greater internal surface area and modified pore size distribution. The coal produces the activated carbon is mostly preferred for the saline environment because of its mechanical strength, and cost-effectiveness. Even though it has limitations in the treatment and effluent reduction. The sodium hypochlorite removal, coal-based granular activated carbon is generally the preferred choice. This type of carbon is suitable for liquid treatment applications and offers a good balance of adsorption capacity, hardness, and flow resistance (Villota et al., 2019).

The special cake resistance plays a key role in the adsorption of Activated Carbon (AC) by the membrane filtration. In the Carman–Kozeny equation, when there is a minor modification in porosity, it creates a major change in special cake resistance. Furthermore, it is strongly dependent on the particle size, especially diameter. As a result, the floc size distribution shows that a significant change in special cake resistance can result from a comparatively little change in porosity. Furthermore, the effective particle diameter has a significant impact on special cake resistance (Lesage et al., 2008).

Because heavy metallic ions are light-dense and have functional groups on their morphology, the many biomasses that produce activated carbon (AC) in modern times face difficulties with the molecules' affinity and limited recovery of heavy metallic ions. Furthermore, the metal ion adsorption capacity of activated carbon is influenced by both its porous structure and surface characteristics (Zeng et al., 2020); Sun et al., 2009; Hasan et al., 2008). The availability of poly aromatic compounds ring structure and chlorinated biphenyl multi ring deposits were reduced dramatically due to the Carbon mixture composition (Zimmerman et al., 2004, Sewu et al., 2019).

There is enough activated carbon is required in homogenous conditions to mix the pollutants. The ultrafiltration membrane unit's cleaning procedure keeps the activated carbon in place. The majority of the time, fine molecules of activated carbon are used in the reaction unit. This unit's fine powdered AC can be removed and used again in biological reactions. Backwash occasionally occurs when the bed material in a packed bed column is large enough to be stored in the column (Baresel et al., 2019, Chen et al., 2012).

Theare are few hydroxyl groups such as Amide, Amino present in chitosan, a naturally occurring polysaccharide). Seabeds has been utilized extensively as an affinity material to remove potentially toxic elements from effluent, because of its potent chelating activity (Rinaudo, 2006, Oliveira et al., 2019). The hydrothermal liquefaction makes the greater impact on modelling and simulation for Ulwa porifera for the bio-yield separation using ASPEN-HYSYS (Thirumalaikumar and Jaikumar, 2024). The Eco friendly bio oil yield is achieved by Hydrothermal liquefaction at 280 °C and Solid liquid ratio of 1:0.75 achieved by maximum yield 23.5% (Ramaiya and Vasudevan, 2024) .

The marine vessel impurities and industrial wastewater - connected contaminant-rich seawater are unacceptable for human utilization. The leading promising technology is using activated carbon to enhance the adsorption. It is a critical method to remove the impurities and contaminants of seawater desalination. It assists in minimizing the water quality compromise. This procedure was performed by running the saltwater through an activated charcoal bed, which eliminates pollutants and contaminants and leaves behind pure water. The activated carbon (AC) is used for seawater treatment. This carbon material is highly porous and effective to remove the odor, color, organic pollutants, residual chlorine, and certain micro-contaminants below high-salinity environment. (Hall et al., 1966; Reed and Matsumoto; 1993 and Al-Khateeb et al., 2014).

The Chitosan-coated activated carbon produced from *Sargassum horneri* (CSAC) was formulated by organic compound initiation and outer layer change. The composite was calculated for the recovery of Chemical compound Cr (VI) present in the solution. Based on the literature information the excess amount of Cr (VI) adsorption capacity of 20.5 mg $g^{-1}$ was obtained at 303 K. Using Freundlich isotherm model The equilibrium data are investigated (Zeng et al., 2020).

Based on the previous study, the AC was investigated for the removal of phenanthrene from the Fresh Water (FW) and Saline Water (SW). The high concentrated (50–200 $\mu$g $L^{-1}$) phenanthrene in the presence of SW increases the sorption process by activated carbon. However, at lower concentrations (3–10 $\mu$g $L^{-1}$), sorption was reduced, resulting in lower uptake from SW than from FW (Zimmerman et al., 2004). The Effluent standards and performance tests for sewage treatment plants treated by many sources palm seed, biomaterials are used as activated carbon, even though ocean related material investigation is limited (Srivastava et al., 2021).

There are a few factors that perform a essential role in the continuous operation and backwashing of seawater treatment, such as adsorption capacity, flow and pressure drop performance, followed by durability (Liu et al., 2013, Lima, 2018). Once the mentioned parameters are optimized, AC becomes a consistent material in pretreatment and improvement steps in desalination, aquaculture, offshore platforms, and shore industrial facilities. There are studies available on the impact of AC on wastewater purification. However, studies on marine resource seashell-produced activated carbon with layer coating are limited. Therefore, this article investigates the function of Activated Carbon (AC) in wastewater treatment and how it contributes to ecological protection. This research can improve the effectiveness of naturally produced activated carbon used for water purification, including revival techniques, in addition to the material's lifetime.

The research mainly focused on the following key targets based on the experimental investigation to identify the carbon yield and physicochemical properties of the prepared material. To estimate the adsorption functioning of the eco-friendly activated carbon materials impact on laboratory-produced $K_2CrO_4$ and acetaminophen. In addition, the relationship with maritime sector applicability in the sewage water treatment process and the cost-effective water purification method with low operational costs and maintenance requirements.

## 2. Materials and Methodology.

### *2.1. Materials.*

This study is mainly focused using marine resource seashell and date syrup, it is collected from the northern coastal area in Oman. The coastal line has the substantial amount of seashell availability motivate towards the Sustainable goals (Oman Vision.2040), furthermore transportation feasibility to engage renewable solution for the environment. The marine resource dried seashells were then ground and screened into different particle sizes, large, medium and small fractions. To investigate the effect of particle size variation on the adsorption performance, the particle size was varied as smaller particles offer a higher surface area while larger particles offer better mechanical strength.

Gulf Countries are larger producer of dates. In that, Sultanate Oman is one of the leading producers of dates and producing plants. The required date syrup is prepared from the waste dates from farm and packing industries. The amount of waste dates in this gulf area, roughly 5% to 20% of harvested dates are classified as due to the damage, unmarketable waste depending on the variable zone. The collection of unused dates after washing is crushed with aid of water, filtered then collected under various concentrations. The dryness confirmation and concentration of date syrup is confirmed by analytical instruments.

### *2.2. Experimental Methodology.*

This research begins with the collection of seashells and extraction of date syrup. The collected seashell washed and dried in the muffle furnace at 80 °C for 2hr in the Analytical (Algae research) lab in PE. The washed seashell is clearly confirmed with the absence of impurities and deposits presents on the shell surface (Figure 1.1.). The moisture reduction on the surface of the seashell gives better aid for the Date Syrup-DS, (deposition) coating on the shell. The dried marine resource seashell is fed to the crusher for the size reduction and sieve unit to achieve the required particle sizes (Figure 1.4.). The crushed seashell is transferred into the container for uniform mixing with the various composition of seashell and date syrup for the following proportions (1:0.25; 1:0.5; 1:0.75; 1:1 and 1:2) (Figure 1.2.). The experimental studies are conducted under three different heating modes such by Open Flame (Coal), Fire (Gas burner) heating (Figure 1.3.), and Hydrothermal Liquefaction Reactor (Figure 1.4) under nitrogen inserting conditions.

The experiment is conducted for the various compositions for the following methods such as open flame (Coal) method, Fire method and HTL method for the operating conditions temperature of 2 MPa and 280°C to 320 °C. Two hundred grams of weighed dried seashells and 200 ml of date syrup were taken

Figure 1: Experimental materials and apparatus used in the preparation and pollutant-removal analysis of date-syrup-coated seashell activated carbon.

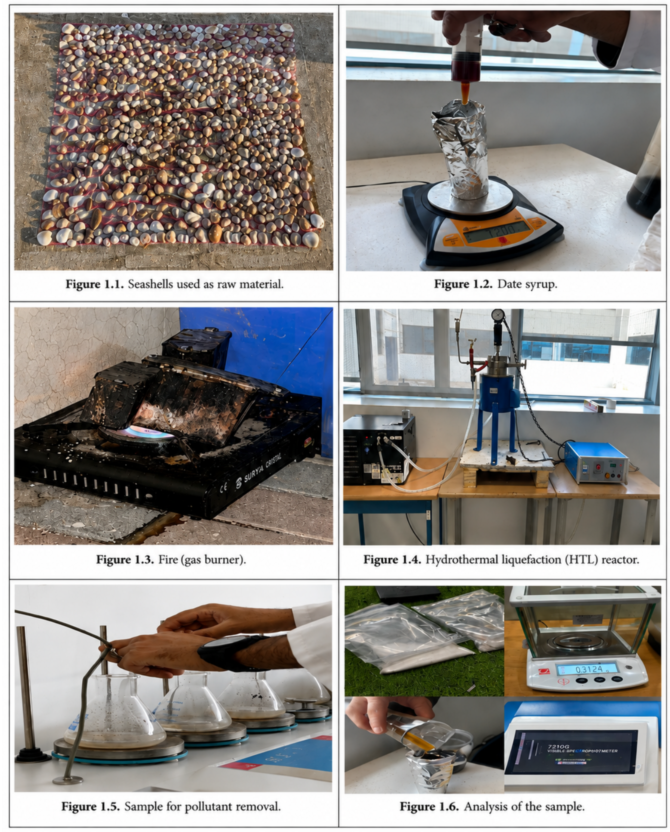


**Figure 1.1.** Seashells used as raw material.
**Figure 1.2.** Date syrup.
**Figure 1.3.** Fire (gas burner).
**Figure 1.4.** Hydrothermal liquefaction (HTL) reactor.
**Figure 1.5.** Sample for pollutant removal.
**Figure 1.6.** Analysis of the sample.

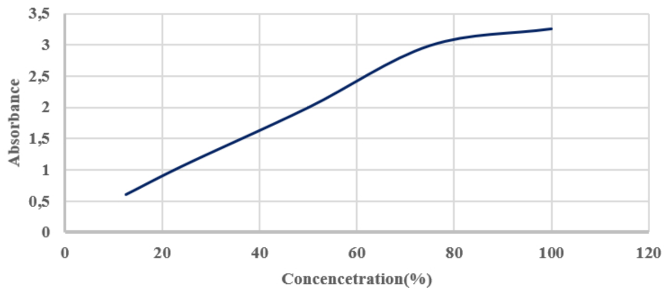
Source: Authors.

into the working container, after proper mixing the samples are collected in in sample container kept in the open flame (Coal) using fire gun temperature is maintained 280 °C after the reached the required temperature the date syrup coated layer Activated Carbon is produced. The same procedure is repeated for fire (Gas burner) method (Figure 1.3.), and HTL reactor (Figure 1.4.) method is under operating conditions (280 °C to 320 °C). The converted date syrup coated seashell is after chemical activation is converted as Activated carbon. The date syrup coated AC with different dosage added with the laboratory grade Acetaminophen, Potassium chromate effluent (Figure 1.5.) and sewage water concentration removal efficiency is investigated (Figure 1.6.).

## 3. Results and Discussion.

Figure 2 shows the relationship between absorbance and acetaminophen response for the standard solution, indicating that as the concentration increases from 10% to 65%, the absorbance response is investigated for $K_2CrO_4$ as well. The above figure represents the standard stock solution responses for the UV spectroscopy (Ramesha et al., 2011).

Figure 2: Absorbance vs. concentration of Acetaminophen.

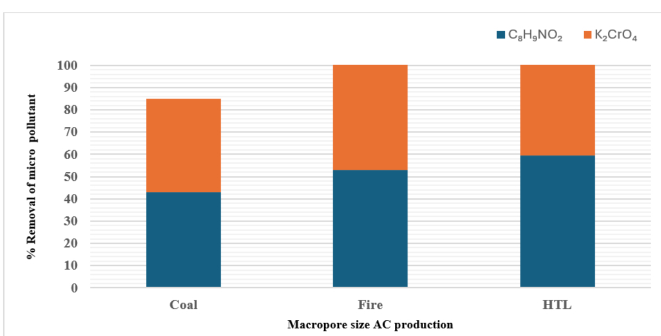



Source: Authors.

### 3.1. *Effect of DS coated macropore size AC on pollutant removal*

The below Figure 3 discusses Date Syrup (DS) coated Marine resource seashell produced macropore size activated carbon used for pollutant removal, 43% for open flame (coal), 53% for fire (gas burner), and 59.5% for Hydrothermal Liquefaction - produced activated carbon for acetaminophen. In the case of $K_2CrO_4$ pollutant removal using macro-size AC, 42% was achieved for open flame and 62% for the HTL process. The amount of removal was substantially good when compared to previously published work (Nguyen et al., 2020, Liu et al., 2013).

Figure 3: Percentage removal of micropollutant using macropore size AC.

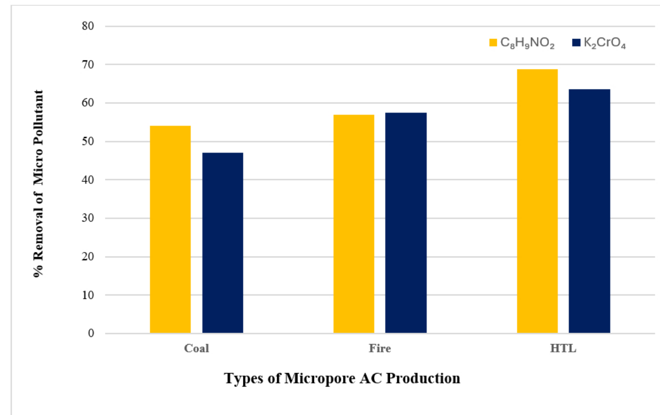



Source: Authors.

### 3.2. *Effect of DS coated micropore size AC on pollutant removal*

Figure 4 illustrates the percentage of pollutants absorbed with micropore sized Activate Carbon. The acetaminophen removal percentage increased from 54% to 68.75% from the coal to the HTL process. It increased by 27.5% and is higher than the open flame (Coal) heating process. Hydrothermal liquefaction gives a better surface area increment for date syrup-coated seashell-produced AC of micropore size. For potassium chromate, Hydrothermal Liquefaction technique improved pollutant removal from 47% to 63.5%. The percentage removal of pollutants was substantially higher due to the date syrup layers formed by the HTL reaction. It is in great agreement with past studies (Li et al., 2019, Al-Khateeb et al., 2014).

Figure 4: Percentage removal of micropollutant using micropore size AC.

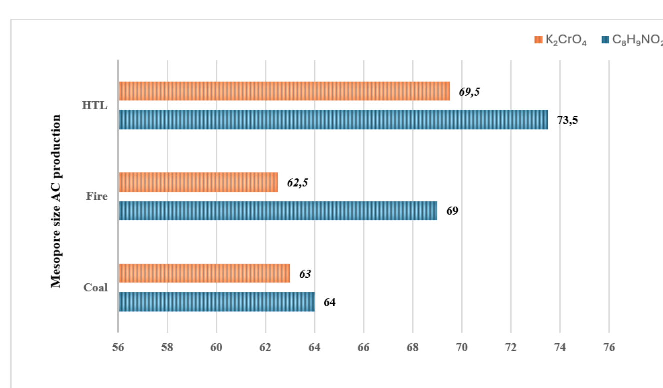



Source: Authors.

### 3.3. *Effect of DS coated Mesopore size AC on pollutant Removal*

The percentage removal of wastewater pollutants is carried out using small, medium, and larger-sized date syrup-coated marine seashell-produced AC. There are a few observations explained below. The micropollutants (acetaminophen and potassium chromate) are removed by mesopore-sized date syrup-coated activated carbon produced from coal open flame, fire (gas burner), and hydrothermal liquefaction processes. Figure 5 clearly states that the percentage removal of the micropollutant acetaminophen is 73.5%, and the potassium chromate removal percentage is 69.5%. The removal efficiency of HTL is 15% greater than that of coal and fire (gas burner). The removal efficiency of potassium chromate is 11% higher than that of coal, which has an efficiency of 63%. It is in good agreement with the previous literature. In addition, the layer formed on the treated mesopore AC enhances the pollutant removal due to the active pore size and mass transfer, and accessibility when compared to micropore AC (Li et al., 2019, Liu et al., 2013).

Figure 5: Percentage removal of micropollutant using mesopore size AC.



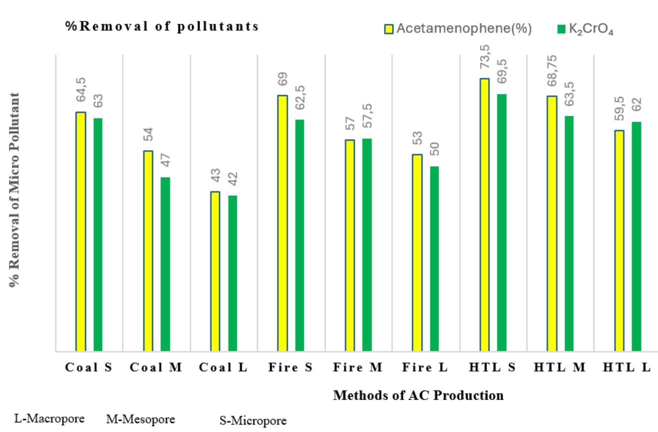

Source: Authors.

### 3.4. Comparative study on $K_2CrO_4$ and $C_8H_9NO_2$ removal

The above Figure 7 shows the comparative investigation pollutant removal using Macropore, Mesopore and Micro pore size of AC. The Macropore size(L) activated carbon pollutant removal from coal to Hydrothermal liquefaction 1.5 times higher than the actual removal efficiency. In case of Mesopore size AC produced from HTL for Acetaminophen 1.4 times higher than the Open flame (Coal). The Mesopore size AC gives the maximum recovery of 73.5% of the Acetaminophen under 280 $^oC$ and 2 MPa.

The adsorption performance of Oxalic-acid-activated date-syrup-coated seashell carbon was evaluated for the removal of acetaminophen and potassium chromate. The results clearly reveals that the carbonization method and precursor particle size significantly influence the adsorption efficiency. When investigated carbonization methods, the HTL derived adsorbent is expected to show maximum removal performance due to the controlled thermal conversion, improved development of reachable pores, and protection of oxygen-containing surface functional groups. In comparison, direct carbonization using open flame (Coal), fire (gas burner) flame may produce less uniform heating and identified overheating, that is affect the pore development and surface chemistry (Nguyen et al., 2020, Yu et al., 2012).

Figure 6: Percentage removal of micropollutant using different sizes of AC.

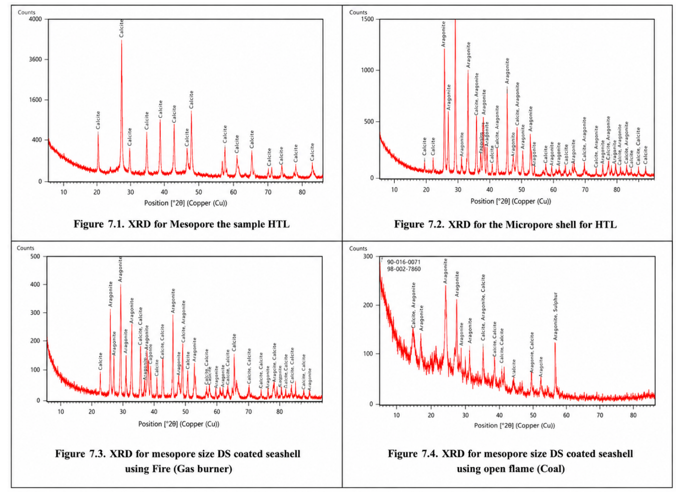



Source: Authors.

### 3.5. XRD Investigation for (Date syrup coated Seashell) AC

The XRD refers to the Date syrup (DS) coated with marine source seashell produced chemically activated AC utilization for Acetaminophen pollutant for different sizes (Micro, Meso and Macropore) of the materials. It clearly reveals that the Aragonite and Calcite behavior during the Hydrothermal liquefaction Process. The Mesopore structure (Figure 7.1) behavior on Acetaminophen removal efficiency confirmed by the Aragonite peak at $2\theta$ (28°) angle 3000 au, The XRD patterns showed strong diffraction peaks corresponding to calcite and aragonite, confirming the presence of crystalline $CaCO_3$ derived from the seashell and confined layer of date syrup (Masukume et al., 2014, Reddad et al., 2002). Similar crystalline aragonite phases

Figure 7: XRD investigation of date-syrup-coated seashell activated carbon under different pore-size and processing conditions.




Source: Authors.

have been reported for seashell-derived adsorbents. The broad and weak diffraction features indicate the presence of a poorly amorphous carbonaceous phase formed during HTL and when compared to micropore activated AC. The combination of the carbonaceous phase and $CaCO_3$ minerals provide a heterogeneous surface for Acetaminophen and adsorption. In case of Figure 7.2. XRD peaks refer to the micropore size AC performance of Acetaminophen and $K_2CrO_4$. The removal efficiency is lower when compared to mesopore due to the active pore size confirmed by BET. Figure 7.3. and Figure 7.4. shows the XRD for mesopore size DS coated seashell using open flame (Coal) performed lower due to the distraction of the flame and functional group. Therefore, the collected DS coated Seashell has performed better removal for the mesopore structure it has good agreement with the previous studies (Yu et al., 2012, Li et al., 2019, Liu et al., 2013).

## 4. Conclusion.

The suitable operational temperature for the hydrothermal liquefaction process is 280°C and 2 MPa. Acetaminophen 1.4 times higher than the open flame (Coal). The Mesopore size AC gives the maximum recovery.

The XRD also confirmed the mesopore AC activity in the micropollutants Acetaminophen and $K_2OCr_4$. The Mesopore structure behavior on Acetaminophen removal efficiency confirmed by the Aragonite peak at $2\theta$ (28°) angle 3000 au gives the maximum recovery of 73.5% for Date syrup 85% concentration. This mesopore enhances mass transfer and activation sites engagement with the reaction for the pollutant removal when compared to Open flame and Fire (Gas Burner).

The Future direction could be in the form of multiple coating layer on marine source and different inert gas impregnate impact and kinetics can be investigated.

**Acknowledgement.**

The author acknowledges the valuable contribution of the Algae Research Lab team and extends special thanks to Dr. Meena Madhavan, Assistant Professor, LTM Department, IMCO-National university and Dr. Faizal Al Marzhuqi, Support Service department, UTAS, Sohar. Furthermore, the author gratefully acknowledges the support provided by the Central Analytical and Applied Research Unit (CAARU), Sultan Qaboos University, Oman.

**Conflicts of Interest.**

There are no conflicts of interest related to this work.

**Graphical Abstract**

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