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Analysis on Preparation, Application, and Recycling of Activated Carbon to Aid in COVID-19 Protection

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Abstract: Activated carbon (AC) is an extremely porous carbonaceous adsorptive substance which has a rigid carbon matrix with high surface area and broad functional groups. The structure is connected by chemical bonds; arranged irregularly, generating a highly porous arrangement of corners, crevices, claps, and cracks between the carbon layers. Activated carbons are produced high-temperature and chemical activation of waste biomass. The pores in the lattice network of activated carbon permit the removal of impurities from gaseous and liquid medium through adsorption. At present, the COVID-19 disease is the prime concern around the whole world because of its exponential infections and death rate. There is no medicine for this virus, and protection is the only remedy to survive from this contagious disease. Using a face mask is one of the best methods to get rid of COVID-19. The mask combined with activated carbon can be beneficial for adsorbing and disinfecting the virus as it is the versatile adsorbent for the elimination of the organic, inorganic, and pathogenic contaminants.

Keywords: Activated carbon, adsorption, recycling/regeneration, COVID-19, coronavirus, SARS-CoV-2.

1. Introduction

Before 3750 BC, the use of carbon was started in the production of bronze of zinc, copper, and tin by the Egyptians and Sumerians. In 1773, Car Wilhelm had recognized the absorptive capacity of carbonaceous substances from diverse precursors. The first commercial marketing of manufactured activated carbon (AC) was introduced in 1911 in Austria. AC has other names with activated coal, activated charcoal, and carbo enables [1]. It is one of the best adsorbents for its enormous adsorptive capability and a significant amount of porosity. One gram of activated carbon can produce around 400–1000 square meters of the surface area [2]. The most common uses of ACs are for water treatment, gas masks filter, ventilators, odor control, pathogen removal, metal purification, medicine, sewage management, compressed air filters [3].

Any material which has a high carbon and less inorganic contents can be utilized as the raw resources of activated carbon. Waste biomasses are used mainly for the production of AC with better adsorption capability and adequate mechanical power [4]. Lots of precursors are used for obtaining sufficient activated carbon from waste biomass

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like Acacia species, paddy straws, coconut, bamboo, bagasse, fruit shell, fruit skins, etc. [5]. The use of waste biomass for ACs sources is advantageous as it is cheaper, abundant, and non-toxic [6]. Adsorption capacity is the main characteristic of activated carbon in its porous arrangement and chemical groups in the surface area [7]. The energy that comes from the burning of fossil fuels creates greenhouse gases that can be minimized by activated carbon [8].

Currently, the novel coronavirus disease 2019 (COVID-19) is a great threat to the whole of humanity. It is an infective pneumonia illness that occurred by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). This virus was initially perceived in December 2019 at the Wuhan city, Hubei Province, China [9]. Within a short period, it was spread in 215 countries and considered as a pandemic disease for infection and mortality rates. COVID-19 is a novel beta RNA virus of 60-140 nm diameters with spine type projection. It causes a severe syndrome of respiratory diseases with fever, breathing problems, cough, and a few gastrointestinal symptoms [10]. The coronavirus can spread by the human-to-human conduction through nose, mouth, and eyes, mainly for coughing and sneezing [11]. To date, no medicine or vaccine has invented for COVID-19 disease entirely. Protection is the only primary remedy to minimize the transmission of the virus by wearing a face mask, using hand sanitizer, and maintaining physical distance (Figure 1) [12]. Since the virus enters the human body through the nose and mouth, it can prevent by wearing a face mask.

Fig.1 - Protection ways from COVID-19 [13]

To reduce the exposure to the virus, numerous types of respiratory safety are used like N95 respirator masks, surgical masks, cotton cloths, etc. All these masks cannot filter and absorb the virus, bacteria, dust, and toxic gases. Among them, the N95 respirator mask can filter viruses, bacteria, and dust. But it cannot work appropriately for small particle size and high breathing rates [14]. It is highly essential to design the respiratory protector properly, which can filter viruses, bacteria, toxic gases, and dust. Mask s made with activated carbon can filter the pathogens, smokes, dust, and hazardous gases [15].

2. Preparation of AC

The activated carbon preparation follows two main phases; the first stage is the carbonization, and the second stage is the activation. The carbonization of the biomass occurs through the pyrolysis process which produces biochar [16]. The carbonaceous materials are prepared by eliminating the volatile matters through thermal decomposition in this stage. Temperature, heating rate, gas flow rate, and the residence period are the main parameters [17]. As biochars show lower adsorption capability, an activation procedure is important to develop the pore volume and the surface areas. Initially, the disordered carbon has removed, exposed to the activating agents, and improves the porosity. Lastly, the existing small pores are broadened to bigger sizes through the burning of pore walls. It increases the in-between pores and the macro-porosity to reduce the micropores volume [18]. The degree of burn-off and the grade of activation is a significant extent for preparing the porous AC. The primary activation can be done by a physical, chemical, physiochemical, or microwave radiation processes [19]. Activated carbon is made from biomass with the following procedures.

2.1 Pyrolysis/Carbonization

The pyrolysis or the carbonization is a thermal degradation process to decompose the biomass at higher temperatures under an inert environment. In this process, the volatiles and non-carbons (hydrogen, oxygen, and nitrogen) are removed and enhanced the fixed carbon content of the biochar [20]. During the de-volatilization process, small pores are developed, which can be deposited by tarry materials at higher temperatures [21]. This deposition cause collision in the tarry elements and the pore walls for the hydrocracking of the elements [22]. Table 1 shows the four phases of the carbonization procedure [4].

2.2 Conventional Heating

One of the most appropriate preparation methods for manufacturing activated carbon is conventional heating. During conventional heating, heat is shifted to the examples by conduction, convection, and radiation devices [23]. The particle surface is heated, encouraging a thermal gradient between the core and the surface of each particle.

Conventional heating is slow and inhomogeneous in which the surface and corners are much warmer than materials inside [24].

Table 1 - Four phases of carbonization procedure

Phase	Temperature (°C)	Reaction type	Procedure
1	≤ 200	Endo-thermic	Primary heating of materials to eliminate the moisture content
2	170 - 300	Endo-thermic	Produce pyroligneous liquids, light tars, and gases (non-condensable)
3	250 - 300	Exo-thermic	Major elimination of the pyroligneous liquid and tars
4	>300	-	Elimination of the volatiles and the non-carbon components to increase the fixed carbon percentage of the biochar

2.3 Physical Activation

During physical activation, the raw materials undergo carbonization under a temperature of less than 700 °C, in an oxygen-free environment. The physical activation response occurs between the oxidizing gas and carbon atom, which produces pores as different portions of the char structure respond quicker than the rest. However, due to the period and a large amount of energy needed, physical activation is not appropriate all time. Moreover, a massive amount of the inner carbon mass is demolished to acquire the pore structure [25]. Physical activation has accompanied by two stages. In the first stage, carbonization proceeds to remove all volatile substances in small temperatures from the precursor. The activation of the gained carbonized material undergoes at higher temperatures using inert gasses, which are optional in the second stage. The burning of carbonaceous elements may be prohibited in the existence of steam (H_2O), Nitrogen (N_2), CO_2, and Argon (Ar) or the combinations of these gases [26].

2.4 Chemical Activation

Chemical activation provides several benefits, because the process is a single step mixture and activation, achieved at temperatures that are lower than physical activation, and thus, development of a higher quality of porous structure [25]. Furthermore, the chemicals added for activation can be simply regained. Chemical activation is typically favored because of its low temperature, uncomplicatedness, well advancing of the porous structure, higher production, and quicker activation time. But, problems regarding this technique involve the necessity to rinse the final product of the remaining inorganic substances, which can result in pollution difficulties [27]. Some acids (H_3PO_4, HCl, HNO_3, and H_2SO_4), bases (NaOH, KOH, and K_2CO_3) and few oxidants (H_2O_2 and $KMnO_4$) are generally used for the activation procedure. The first benefit is that acid action enhances the properties of AC with the surface area and the porosity that accredit the removal efficiency of the pollutants to the carbon surface. The second advantage is that it can create or enhance numerous functional bunches (carboxylic group, amino acids, oxygen cluster, etc.) on the exterior of the activated carbon [28].

2.5 Physiochemical Activation

In this process, both the physical and the chemical activators are used instantaneously afterward, the carbonization. The activation mostly happened at a higher temperature of 600 - 850 °C with the existence of chemicals, such as H3PO4, ZnCl2, KOH, CO2, or H2O (steam). Though it is costly and time-consuming, physiochemical activation can create activated carbon with significant surface properties. The joint activation process will impose on the pore opening, which leads to a well-built porous structure. For instance, KOH with CO2 can create higher macropores and mesopores within the matrix of activated carbon [18].

2.6 Microwave Activation

In the AC production process, the microwave (MW) activation became a feasible substitute than conventional methods. It has some exceptional features like selective, quick, eventual heating to the sample, prompt response, and precise regulator. The significant working constraints are MW radiation strength, precursor properties, activation time, and chemical constituents [27]. In the microwave process, the energy transferred inside the particles as heat through the dipole alignment and the ionic conduction. The particle with dipole moments is associated with the opposite course from the force applied for high voltage. Therefore, high-temperature difference developed in the molecules inside and outside, that make AC more functioning and faster [29].

3. Types of AC

Activated carbons (ACs) are categorized into six classes according to their size, preparation methodology, and application as follows [1];

- Granular activated carbon (GAC)
- Powdered activated carbon (PAC)
- Extruded activated carbon (EAC)
- Bead activated carbon (BAC)
- Impregnated activated carbon (IAC)
- Polymer-coated activated carbon (PCAC)

Activated carbons that are chemically and physically activated, ordinarily present in three shapes, which are granular AC, powdered AC, and extruded AC. GAC has a rough formed by crushing and sieving, which vary in 0.2 to 5 mm inner dia. GACs are stable and hygienic to grip the amounts of gas and oil to a steady distinction. It can be reactivated and recycled [30]. PAC owns the particle size of 5 to150 angstroms. It has little production expenses, which are flexible and improved. Palatable oils are frequently cleansed by PAC and continuously in combination with the earth. EACs are cylindrical pellets which diameters from 1-9 mm. Significant applications of EACs are in gas purification, solvent recovery, gold rescue, and automobile discharges regulator [25].

4. Characteristics of AC

AC is the carbonaceous material of higher porosity and significant surface area with the vast functional area [31]. Different parameters like pore diameter, hardness, density, iodine number, and ash contents make them appropriate for specific applications. Also, ACs have remediable pores with tunable surface chemistry, chemical/thermal steadiness, and high accessibility [32]. AC contains different functional groups of aromatic rings that maintain the chemical properties. These groups can be initiated on carbon structure to work through chemical, thermal, and hydrothermal treatment. AC by KOH can enlarge the surface area up to 1200 m^2 per gram by the elimination of acidic constituents, which might close the pores [27]. The removal efficiency depends on the pore size, surface area, hardness, and density of the AC with the concentration, solubility, chemical, and magnetism affection of the pollutants [33].

The most dynamic and thorough requirements for ACs in purification methods are connected to the contented of inorganic constituents [34]. AC for gas and air purification has a BET surface area between 800 - 1500 m^2 per gram, where for water purification within the range of 500 to 1500 m^2/g [35]. Organics has been adsorbed to the exterior of AC uses for a long time; allow the accommodation of the constituent resulting in biodegradation of organics. ACs can recollect volatile organic compounds on their surface and stop them from releasing into the atmosphere [36]. The size of the particles is accountable for guiding the availability of the adsorbate to the pores of AC. In contrast, the solubility controls the level of hydrophobic connections between adsorbate and the surface of AC [37].

5. Pores of AC

An important characteristic of AC for removing pollutants is their pores. AC involves ‘‘pores’’ with variable sizes and shapes. According to the IUPAC categorizes pores [38] are

- Macropores (Diameter > 50 nm)
- Mesopores (2 ≤ Diameter ≤ 50 nm)
- Micropores (Diameter < 2 nm)

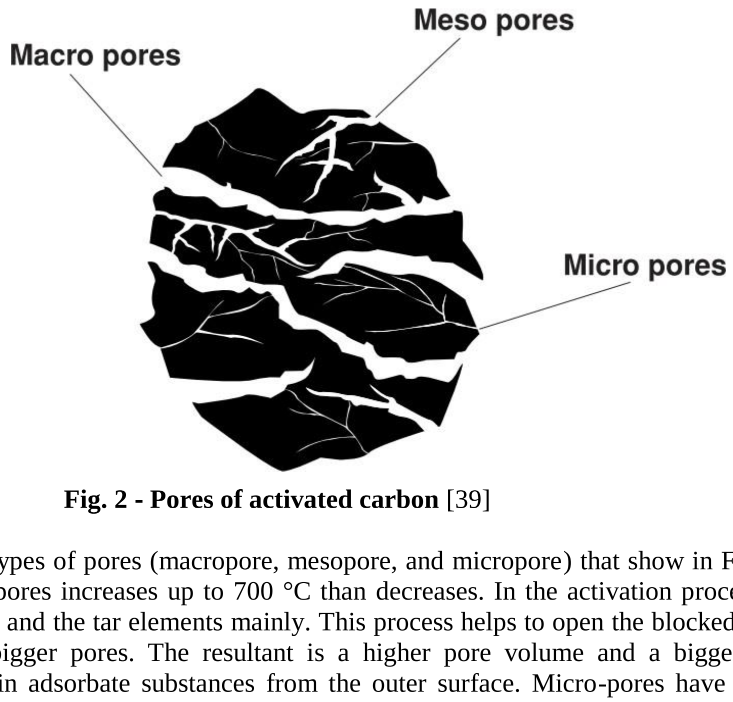

Fig. 2 - Pores of activated carbon [39]

ACs contains three types of pores (macropore, mesopore, and micropore) that show in Figure 2. In carbonization, the volume of the micropores increases up to 700 °C than decreases. In the activation process, the reaction occurred between oxidizing agents and the tar elements mainly. This process helps to open the blocked pores, expands the small pores, and forms new bigger pores. The resultant is a higher pore volume and a bigger surface area [40]. The macropores aid to restrain adsorbate substances from the outer surface. Micro-pores have advanced ratios for their surface area to pore volume, compared to mesopores and macropores [41]. Mesopores help transmit the adsorbate elements to the inner particles where micropores can catch. Macro-pores are utilized in trapping larger impurities, and micro-pores are applied to captivate the minor molecules [42].

6. Adsorption of AC

AC adsorptions go through three primary stages. First, the materials are adsorbed to the exterior of the carbon matrix. Second, materials transferred to the inside of the carbon pores, and third, materials adsorb the internal walls of the carbon [42]. Adsorption occurs when pollutants are fascinated by the carbon pore, which happened if the carbon pores are slightly bigger than contaminant size [39]. Two types of absorption are usually ensuing, physical adsorption and chemical adsorption as follows,

6.1 Physical Adsorption

The physical adsorption occurs when the surface of carbon crystal attracts the contaminants via Van Der Waals force. Contaminants a to the surface of the AC, where large particles were stuck in tinnier holes [39]. Physical adsorptions are reliant on the concentration of the contaminant in the gas flow, and the pollutant to be adsorbed. Molecules are fixed to the surface of the carbon by intermolecular attraction forces [43]. This adsorption happens inside the pores to own radius of a few times larger than the molecular length of the adsorbed molecule. Pores that are tinier than the molecular impurity sizes are unreachable and do not contribute to the adsorption progress [44].

6.2 Chemical Adsorption

Chemical adsorption is defined as the straight response of the adsorbed molecule to the active surface of the activated carbon. Chemical bonds are formed between the surface of the char and the adsorbate [45]. The functional groups of the carbon surface which carry the oxygen and other electrons participate in this process. If the molecules are adsorbed chemically to the carbon surface, the process is called chemisorption [44]. The adsorption is the combination of pollutants with the surface of the AC pores. The chemical materials existing on the surface of the openings rely on the activation method, a natural resource used, and post-treatment of AC [39].

7. Factors Influencing Adsorption

The factors affecting the adsorption are characteristics of adsorbent are as follows

- The size of the internal surface area
  Activated carbon has the high surface areas which provide high adsorptive capabilities for molecules in some gases and solvents. The more elevated surface is essential for the adsorption of bigger molecules [46].

- Pore size
  Pore sizes affect the adsorption of the pollutants are in two ways. Firstly, adsorption capacity increases with the reduction of pore size as the contact points increase between the adsorbate and surface. Secondly, the size rejection confines the pollutant adsorption of a specific type of pores, which are too low [47].

- Chemical properties
  In the activated carbon, the existence of the sulfur and nitrogen groups donated the alkaline behaviors, while the oxygen and hydrogen groups added the acidic nature. The higher adsorption of the positively charged pollutants on the AC holding higher O and H groups is constant, where the majority of the negatively charged in acidic carbon [48].

- Molecular characteristics (Chemically)
  The surface functional groups have an important involvement in the adsorption of activated carbon by strong chemical interactions, like Lewis acid-base interactions, electrostatic attraction/repulsion, p-p EDA interactions, hydrogen bonding, and cation–p bonding [49].

- Molecular structure
  Adsorption capability of organic vapors to the activated carbon increased for the higher molecular weight of the adsorbate [50].
- Hydrophilic performance
  For Log-scale adsorption, the sorption coefficients have a positive correlation for hydrophobic compounds and a negative association for hydrophilic compounds [51].

- Polarity
  The adsorption capacity of AC decreased with the increase of polarity and saturation air pressure [50].

- Adsorbate concentration
  The adsorption capacity of the AC increases exponentially with the initial concentration. The removal performances were high at a lower level, while the uptake affected the concentrations increased [52].

- Temperature
  The increases in the temperature make the removal efficiency higher by activated carbon. It is the arrangement of the activated transmission and the rise in surface area. Activated carbon is widening and deepen in micro-pores, which create more surface area for adsorption [53].

- Composition of the mixture
  AC has the potential to be less expensive for hot gas mixture cleanup sorbent like adsorb H_2S from high-temperature coal gas stream [54].

- pH value
  The pH values play an essential role in the adsorption by activated carbon. It is affecting the solubility of the adsorbate by changing the surface charge of the adsorbent [55].

- Relative humidity for the gas phase
  Activated carbon performed in a better way for nitric oxide (NO) conversion and adsorption in dry conditions. Conversion can be compacted up to zero if the relative humidity increased by 50% [56]. The moisture contents decrease the catalytic adsorption of the NO on activated carbon by lodging the oxidation sites, which reduce the efficiency of the NO conversion [57].

8. Applications of Activated Carbon

Activated carbon is the cheap and environment-friendly adsorbents for eliminating the contaminants from water and air in so many sectors as per Figure 3.

Fig. 3 - Applications of AC in different sectors [58]

8.1 Water Purifications

AC is one of the best adsorbents to remove pollutants like dyes, metals, pesticides, etc. from wastewater. The dyeing industries produce around 150,000 tons of dyes into sewage that increases the poisonousness and cancer-causing assets [59]. Heavy metals are also one of the utmost dangerous water pollutants for the human body. The elimination of heavy metals by AC is economically promising and requires simple methods; thus, AC is extensively utilized to process water with heavy metals [37].

8.2 Air Cleansing

Activate carbon can clean the environment by absorbing the harmful gasses (COx, NOx, and SOx) from the air. These pollutant gases cause respiratory diseases, lung infection, breathing problems, cough, heart disease, and paralysis [60]. The removal efficiency depends on the characteristics of the feedstock (petroleum coke, coal, biomass), activators (potassium hydroxide, carbon dioxide, and phosphoric acid), and process variables (activation temperature, the ratio of activator to feedstock) [32].

8.3 Volatile Organic Compounds (VOCs) Capture

During surgical procedures, strong carcinogen smokes are produced, which have volatile organic compounds (VOCs). These surgical smokes are risky for the health of surgeons and operation staff. The activated carbon filter can reduce the adverse effect of surgical smoke effectively [61].

8.4 Pathogen Filtering

Activated carbon can remove the pathogens (virus and bacteria) effectively. The viruses are connected with the AC through the electrostatic force of attraction between the virus tail and the surface of the carbon. With the higher ionic strength, more viruses adsorbed [62]. AC can efficiently adsorb bacteria and microorganisms. The activated carbon masks are used in the hospital for removing bacterial droplets [15].

8.5 Mask Filter Industry

Activated carbon filters are very useful to be used in mask Filter Company to remove the toxic gas, vapors, and odors. The masks can have the capacity to filter out 95% of the particle with 0.3 microns size. It is eco-friendly and low breathing resistance [15].

8.6 Medical Uses

AC is thought out as the first-line agent in the treatment of poisons, especially after passing some hours after poison intake. Numerous forms of ACs are provided with low protein diets to regulate a few signs of uremia amongst patients by several phases of kidney diseases, tie off urine urea, and the urinary poisons with AC, besides the defecation, generating a density ascent for the constant dispersal of the toxins. It has also been testified to remove urinary poisons by charcoals [63].

8.7 Use in Agriculture

Wine and livestock production by farmers are also dependent on charcoal (activated carbon). It is used as an animal feed, pesticide, and nonagricultural ingredients in livestock production. A processing agent from activated carbon is used in organic winemaking to adsorb brown color pigments from white grape concentrates [64].

8.8 Purification of Alcoholic Beverages

Activated carbon filters can be used effectively to remove the impurities from vodka and whiskey. An activated carbon filter can significantly increase organic purity, while organically impure vodka was passing through at the proper flow rate. As a result, the identical alcohol content in vodka is judged by odor and taste [39].

8.9 Storage of Fuel

Natural gas and hydrogen gas can be stored with the help of activated carbon from the literature. The porosity of AC performs like foam for the various gases. Van der Waal force is acting between these gases and the carbon. Then the gas may desorb at higher temperatures for combustion or extracting hydrogen gas for use in fuel cells. It is a remarkable gas reserving technique as the gases can store at low pressure, small volume, and minor mass [65].

9. Recycling and Handling

The recycling of AC is relatively tight and expensive. As the recycling is involved with the elimination of impurities from AC via hot gas or stem without interrupting the adsorbed pollutants [66]. The AC can be reused once the contaminants are eliminated from the used AC by recovering up to 80% of its efficiency. Rigid raw materials, like stone coal, suggestively could retain well and may recycle a hundred times. The two methods of recycling AC as follows [4],

1) Thermal Recycling with heat completed in this way,
   - The ACs are dried up.
   - The dried carbons are pre-heated to carbonized the pollutants.
   - Activated carbons are revived with 700-1000 °C temperature to maintain the hollow porosity, and thus, carbon can be recycled.
2) Steam Recycling with steam is done as follows,
   - The filters are washed by hot water, descending from above, as these carbons filters continuously progress upward from below.
   - The steam is connected and imposed through the AC with 120-130 °C temperature.
   - Finally, the ACs are back-washed and are ready to use.

No severe human health effects like toxicity or carcinogenicity rise for the contact of a person to the activated carbon. The recommendation is to throughout the used or fresh AC to non-hazardous wastes as they are non-toxic. Attention is warned in the repetition of the consumed Activated carbons. The ACs are applying for drinking water treatments must follow the specification of the World Health Organization (WHO) [36].

10. Activated carbon to aid in COVID-19 protection

The activated carbon filter can protect the COVID-19 disease as it adsorbs virus from polluted deposits. This adsorption happens due to the electrostatic attraction forces between the virus and the functional groups (carboxyl groups and amino groups) of AC [67]. The mask equipped with activated carbon can trap and disinfect the coronavirus by adsorbing the moisture. Once the viruses are caught, the high electropositive ions can disrupt the membrane integrity and essential proteins, which lose the cell capability. The combined activated carbon mask also can minimize the spreadability of COVID-19 disease [68]. Some companies even claim that activated carbon filters masks can filter at least 95% of particles from the air while it fitted tightly [69]. Figure 4 shows the typical diagram of a combined activated carbon mask.

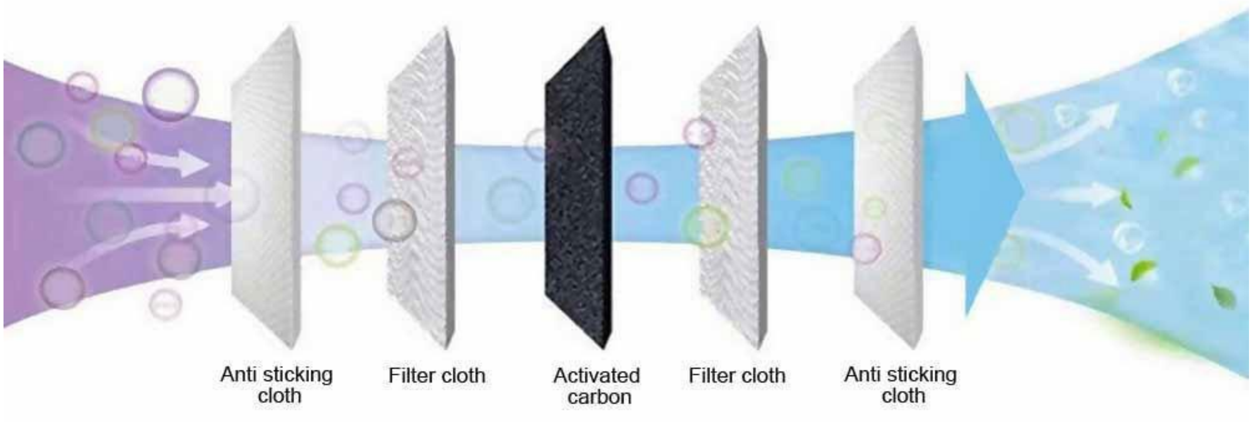

Fig. 4 - Activated carbon with anti-virus micro particle barrier face mask [70]

The removal of the virus through activated carbon mainly depends on

- The hydrophobicity of the virus
- Electrophoretic repulsive force
- Pore size distribution
- The negative charge of activated carbon surface

If the hydrophobicity of the virus surface is more, the removal will be more. For the lower electrophoretic repulsive force between AC and virus, extraction will be higher. Large volume with 20-50 nm pores activated carbons can remove the virus effectively. With the less negative surface charge, the AC can enhance virus removal efficiency [71].

As the COVID-19 has a spike protein with hydrophobic character, the AC can be an efficient adsorbent and filter for this virus removal [72]. The SARS-CoV-2 virus can create a bond with the carbon atoms by hydrogen bonds in the first level, π-π interactions in the second level, and Van der Waals interactions in the third level [73]. In the inhibition of the SARS-CoV-2 virus by the hydroxychloroquine, activated carbon played a significant role. In this process, AC removed the pigments, tannins, and fatty acids. [74]. In the membrane process, activated carbon leads to the best configuration and optimization for eliminating the COVID-19 virus and pathogens from wastewater [75].

There is a significant relationship between death for COVID-19 in the USA and the air pollution associated with dust, smoke, and toxic gases [76]. It also found that in northern Italy, the affected and mortality rate is high for the upper level of air pollution [77]. In the era of COVID-19, there is a massive risk for laparoscopic surgery as this surgical process creates hazardous smokes with volatile organic compounds. It also found that there is a positive relation between surgical smokes and virus transmission. Activated carbon filters can remove the surgical smokes as it has the ability to absorb gas, vapor, and strong-smelling gases [78].

There is no direct relation between the transmissions of Covid-19 with the activated carbon using. Also, nobody has affected in coronavirus while handling the products of activated carbons [79]. Proper care should be taken during the reuse of AC filters according to the rules and standards [80].

11. Conclusion

The whole world is experiencing environmental, economic, and public health problems for COVID-19 disease, air pollution, and waste generation. Activated carbon can be the single solution for its adsorbing capacity and environment-friendly utilizations. It is a cheap, readily available, and versatile adsorbent for filtering viruses, bacteria, metals, dyes, dust, smoke, and toxic gases effectively. Masks combined with activated carbon, protected from COVID- 19, maybe the best solution as it can filter and disinfect the virus. The handling of activated carbon products is also risk-free. Further investigation is necessary to check the performance of activated carbon masks to protect against COVID-19 disease.

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