Biomass activated carbon air filter for particulate removal

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Abstract: An air filter prototype was developed, in which a polyester fabric impregnated with activated carbon (10%) obtained from biomass (banana peels, wood sawdust) was used as the filter medium. FT-IR and XRD were used to characterize the activated carbon. The filtration efficiency of the prototype filter was evaluated using the iodine absorption test, air pressure drops, moisture content, quality factor and statistical analysis. The filtration efficiency of the non-impregnated polyester fabric for $PM_{1.0}$, $PM_{2.5}$ and $PM_{10.0}$ particles were 34%, 19% and 8%, respectively. The use of the banana peel activated carbon impregnated filter increased the removal efficiency of $PM_{1.0}$, $PM_{2.5}$ and $PM_{10.0}$ particles to 63%, 43% and 13%, respectively. In the case of the wood sawdust activated carbon filter, the filtration efficiency was 89%, 37% and 10%, respectively.

Keywords: air filter, activated carbon, biomass, banana peels, wood sawdust.

Filtr powietrza z węglem aktywnym z biomasy do usuwania cząstek stałych

Streszczenie: Opracowano prototyp filtra powietrza, w którym jako medium filtracyjne zastosowano tkaninę poliestrową impregnowaną węglem aktywnym (10%) otrzymanym z biomasy (skórki banana, trociny drzewne). Do scharakteryzowania węgla aktywnego zastosowano FT-IR i XRD. Skuteczność filtracji prototypowego filtra oceniano za pomocą testu jodowego, spadku ciśnienia powietrza, zawartości wilgoci, współczynnika jakości i analizy statystycznej. Skuteczność filtracji nieimpregnowanej tkaniny poliestrowej dla cząstek $PM_{1.0}$, $PM_{2.5}$ i $PM_{10.0}$ wynosiła odpowiednio 34%, 19% i 8%. Zastosowanie filtra impregnowanego węglem aktywnym ze skórki banana zwiększyło skuteczność usuwania cząstek $PM_{1.0}$, $PM_{2.5}$ i $PM_{10.0}$ odpowiednio do 63%, 43% i 13%. W przypadku filtra z węglem aktywnym z trocin drzewnych wydajność filtracji wynosiła się odpowiednio 89%, 37% i 10%.

Słowa kluczowe: filtr powietrza, węgiel aktywny, biomasa, skórki banana, trociny drzewne.

Particulate matter is any substance that is micrometer in size and can penetrate into lungs and enter blood stream, causing severe health hazards [1, 2]. Pakistan ranks second in most polluted countries worldwide with 66.8 μg/m^3 emission of particulate matter due to vehicle, industries, and poorly maintained construction sites. Airborne dust particles can cause respiratory disorders such as byssinosis, diffuse lung disease, dry cough, chronic bronchitis, discomfort in breathing and chest tightness [3]. Motorcars, industries, home appliances that burn energy, and timber fires are all sources of air pollution. Carbon monoxide, particulate matter, ozone, oxides of sulfur and nitrogen are all contaminants that pose a significant risk to public health. Both inner and out-of-door air pollution is responsible to yield respiratory and other diseases and is a substantial cause of morbidity and mortality [4].

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Approximately 2.3 billion individuals in the South Asian region are at risk of inhaling harmful air. The annual mean concentration of $PM_{2.5}$ in India is 40 μg/m^3 (hazardous), while Bangladesh and Pakistan are categorized in the WHO's interim target three groups due to their $PM_{2.5}$ levels being an annual mean concentration of 15 μg/m^3. Although this can be subjective, the most perilous pollutants present in the air are fine particulate matter ($PM_{2.5}$) and ground level ozone [5]. Based on data from 2015, regions with dense populations and significant industrial activities are associated with the highest levels of air pollution. Notably, South Asia accounted for 33% of global deaths caused by outdoor air pollution. This pollution not only impacts human health and wellbeing but also poses a considerable threat to the quality of agricultural products and food security in the area. This concern is particularly critical given that 60% of the world's undernourished population resides in South Asia [5].

Globalization has had a significant impact on industries across the globe, including the textile industry, which has seen a reduction in size. To keep up with globalization, outsourcing and trade have become crucial elements in the textile industry. Currently, clothing and apparel make up approximately 5.7% of total global exports. Experts had predicted that the clothing and apparel trade would reach $1 trillion by 2020 [6].

In 2022, the textile and apparel sector accounted for 3.7% of global goods exports. With economies specializing in the manufacturing and conversion of raw materials into textiles, fiber, and final goods, the sector's supply chains are labor-intensive. Exports of apparel and textiles are often distinguished by their significant regional value-added content [7].

Meanwhile, Pakistan has experienced a significant increase in textile exports, with the Pakistan Bureau of Statistics (PBS) reporting an export value of $19.33 billion in the financial year 2021. This represents a 25.53% increase compared to the previous financial year's value of $15.4 billion [8]. The textile industry is known for being one of the most environmentally damaging industries in the world. It contributes around 5% of all landfill waste and causes 20% of freshwater contamination due to the treatments and dyes used. Air pollution is also a major issue in the textile industry, with pollutants such as Suspended Particles (SPM), Gaseous Oxides of Sulfur and Nitrogen, and other harmful contaminants being released into the atmosphere by boilers, heat bags, and diesel generators. This has a negative impact not only on textile workers but also on nearby human populations [9].

Particulate matter specifically aerosols, when discussing the impact of pollution on textiles. Aerosols have the potential to settle on materials and induce a range of effects, such as soiling, mechanical damage, and chemical alterations. Although there is not much research on the specific effects of aerosols on textiles, studies on paper have shown that the presence of layers of dust can lead to the breakdown of cellulose and undergo chemical changes. This results in larger efflorescence that penetrates between fibers [10].

Industries hold immense significance in numerous countries, serving as vital contributors to employment opportunities, overall economic output, and wealth generation. Pakistan, being a semi-industrialized economy with a robust agricultural base, places significant importance on its textile industry. This sector plays a pivotal role, constituting approximately 8.5% of the nation's total GDP and employing 38% of the manufacturing workforce and 45% of the total workforce, a noteworthy share in a labor-abundant country like Pakistan.

Moreover, Pakistan stands as the eighth-largest textile product exporter in Asia, with textile exports contributing to an impressive 57% of the nation's total export revenue [11]. The textile manufacturing process in certain areas, such as the spinning and weaving sections, results in the emission of airborne dust particles that pose a health risk to workers. A significant proportion of cotton is used in spinning mills, and this results in the dispersal of cotton fibers both within and outside the mills, which contribute to dust and particulate matter in the air. This can exacerbate respiratory illnesses among workers, particularly due to micro cotton resins and other particles, leading to a fatal condition known as "brown lung" (Byssinosis) [8, 12].

In 1938, about 35,000 individuals in the United States were already suffering from "brown lung" disease, while 100,000 more were at risk of being infected. Because of this, the Occupational Safety and Health Administration (OSHA) mandated the textile industry to ensure the protection of their workers from prolonged exposure to cotton dust and its detrimental effects [13].

The Beninese Company of Textiles conducted a study to assess the respiratory health of workers employed in the production sector. The study comprised 656 workers who were regularly exposed to cotton dust and 113 workers with no exposure to cotton dust. The findings indicated that around 44% of both the exposed and non-exposed workers reported experiencing symptoms of byssinosis. An examination was conducted on the spinning workers, and it was noted that those aged between 50 to 60 years old have the highest incidence of byssinosis. The respiratory function of 190 participants was assessed, and among them, 115 workers (60.52%) were found to have byssinosis [14].

In 1995, Byssinosis (brown lungs) was first recorded in India due to the intervention of a non-government organization. Out of 273 chest examinations, 54 (30%) of the 179 people working in dusty areas of a textile mill had byssinosis. 16 (17%) of the ninety-four workers in non-dusty departments were affected. A similar study in Pondicherry found a 6-fold increase in the risk of byssinosis among spinning workers and a 2-fold increase among weaving workers [15].

A study [14] on functioning lungs among the workers in textile sectors in Karachi, Pakistan in which 372 male individuals from 15 various textile mills discovered that over 7.5% of all the workers had a chronic cough. According to this study, chronic cough is defined as coughing for at least 90 days in a row for at least 24 months.

The study [16] aimed to assess the impact of dust pollution on the health, productivity, and illness costs of workers in the textile industry of Faisalabad, Pakistan. This cross-sectional study involved 200 randomly selected textile workers, of whom approximately 62% had been working in the textile industry for 6 to 15 years. The results of the SEM model revealed significant associations between several factors and their impact on workers' health and productivity. Variables such as age, respiratory diseases, overtime work, and duration of employment, mask usage, and dust levels were found to be significant contributors to the health and well-being of textile workers. The study's findings shed light on the complex relationship between dust pollution and various health outcomes, providing valuable insight into the challenges faced by workers in the textile industry regarding their health and productivity.

According to the findings [17], smokers, female workers, and those who work in dusty environments are more likely to suffer from respiratory diseases. The cost of illness approach is used to calculate the economic burden of illness. In addition, in terms of medication, travel costs, and lost workdays because of respiratory morbidities, textile workers incur large financial costs (PKR 4096 per month). The economic cost of disease throws a huge financial burden on workers and their families, given the poor financial condition of most industry workers. By using a filter medium that allows the fluid to pass through while trapping the large solid particles, large particles are removed from a liquid or gaseous fluid through the process known as filtration. End of pipe treatment and source control approaches are exercised for eliminating or reducing the hazards posed by Particulate matter [18].

The particulate matter's passive trap mechanism is like the mechanism of mechanical capture. Gravity, inertial impaction, diffusion, and interception are its primary principles. Furthermore, thickness, porosity (i.e. packing density), face velocity and material structure all have a significant impact on the performance of the filter [19]. Capturing particulates of 0.05-0.5mm with an air filter is difficult, as they are large for diffusion but too little to have sufficient momentum for inertial impaction. Raw materials derived from biomass sources, which can be naturally occurring polymers or synthetic polymers produced through the biomass process. Common examples of natural polymers include silk fibroin, cellulose, chitosan, zein, and soy protein isolate. These natural polymers are often used in air filtration applications to effectively remove particulate matter from the air. Natural polymers and their derivatives have received a growing amount of consideration nowadays because of their excellent biocompatibility, biodegradability, and environmental friendliness [20].

Carbon-based materials play a crucial role across various industries, and activated carbon stands out for its porosity, high specific surface area, and numerous active adsorption sites. It finds extensive use in air filtration processes, effectively removing sulfur and nitrogen oxides, exhaust gases, and volatile organic compounds (VOCs). Moreover, new carbon-based materials like graphene oxide and carbon nanotubes are emerging as promising alternatives for various applications, including particulate matter filtration, opening up new avenues for enhancing air quality [21].

Porous metal-organic frameworks (MOFs) are attracting considerable attention owing to their remarkable characteristics, including precise control over pore sizes, excellent thermal and chemical stability, high porosity, and ease of functionalization. MOFs are constructed from organic ligands and metal ions or clusters, making them versatile and promising materials for various applications. Researchers, including seeded growth, solvothermal freeze-drying, microwave-assisted deposition, electrochemical synthesis, and dip coating, have explored several production methods for MOFs. It is noteworthy that MOFs have been utilized to filter particulate matter after being deposited on specific substrates such as cotton, graphene aerogel, and electro-spun polymer nanofibrous membranes [22].

Various types of filters are available to effectively remove particulate matter, and their selection depends on the specific application and particle size requirements. Among the most used filters are mechanical filters, electrostatic filters, and high-efficiency particulate air (HEPA) filters. These filters offer distinct advantages and are tailored to meet specific air filtration needs [23].

Electrostatic air filters employ an electrostatic charge to draw and capture airborne particles. These filters usually comprise a metal mesh or synthetic fibers charged with electricity. As air flows through the filter, the charged fibers attract and trap particles like dust, pollen, and pet dander. Electrostatic filters are known to be more efficient than mechanical filters, as they can capture particles as small as 0.1 microns in size. However, it is important to note that they are not effective at removing gases or odors from the air. Their primary function is to capture solid particles suspended in the air [24].

According to [25], electrostatic air filters can effectively remove particulate matter from indoor air. The study found that electrostatic filters were able to capture over 90% of particles sized 0.3 microns or larger. A mechanical air filter with pleats, such as a High-Efficiency Particulate Air (HEPA) filter, is designed to effectively remove particulate matter from the air. This type of air filter has high filtration efficiency and can theoretically capture 99.97% or more of dust, fungus, pollen, microbes, and other airborne particulates that are smaller than 0.3 microns (μm) in size. HEPA filters are widely used in various applications, including air purifiers, vacuum cleaners, and HVAC systems, to ensure cleaner and healthier indoor air quality.

Due to its extreme delicacy, the HEPA filter must be transported, stored, and handled with the same care as delicate equipment. Training in proper handling methods should be provided to those who oversee receiving and handling HEPA filters. Every HEPA filter that comes in must be visually inspected [26]. Zhang *et al*. investigated structure and filtration efficiency of two types of HEPA filters, one without additional cleaning and the other impregnated with soot [27].

In India, researchers designed a cost-effective industrial air filter to remove hazardous fumes and unburned carbon particles. The air purification system consisted of four filter media placed vertically in a box along with a brushless DC fan. When these four filters are combined, the smoke emission to the environment is reduced from 77 to 47% (i.e., 61.03%), dust emission from 0.42 to 0.33 ppm (i.e., 76.74%), and CO emission from 3 to 0% [28].

Biomass-derived activated carbon has demonstrated comparable or even superior performance compared to conventional petroleum-based activated carbon in diverse applications, such as water treatment, air purification, and energy storage. The production process involves pyrolyzing various organic materials like wood, agricultural waste, and sewage sludge, resulting in activated carbon with a high surface area and pore volume, making it an exceptional adsorbent for a wide range of pollutants. Beyond its outstanding adsorption capabilities, biomass-derived activated carbon is renewable and biodegradable, presenting a more sustainable option to traditional petroleum-based activated carbon. With the global emphasis on sustainability and environmental preservation, the adoption of biomass-derived activated carbon is anticipated to grow in multiple industries. The synthesis of activated carbon involves two fundamental steps namely carbonization and activation [29].

The utilization of banana peel as a primary source to produce activated carbon presents notable economic advantages and environmentally friendly attributes. Abundantly available and obtainable in substantial quantities from banana processing plants or domestic kitchens, banana peel possesses a significant lignocellulose content of approximately 90.3% (dry weight). This characteristic renders it a promising agricultural biomass waste suitable for the synthesis of activated carbon. The systematic process of producing activated carbon from banana peels. $ZnCl_2$ is utilized as the activating reagent due to its superior specific surface area. After this, physical activation is carried out using heat, which can be achieved through either microwave or furnace heating. Microwave-induced reactions have been proven to be more efficient and expeditious compared to traditional furnaces, as energy is readily converted into heat within the particles through ionic conduction and dipole rotation [30].

Sugarcane is extensively grown in tropical and subtropical regions worldwide, resulting in an annual global production of 1907.02 million metric tons. Bagasse byproducts are frequently burned to generate energy or used as a raw material in the manufacture of paper, pulp, and board. Recent research, however, has shown that bagasse can also be used as a feedstock in the production of biofuels and biochemical [31].

Each type of organic waste is incinerated at a temperature appropriate for its properties and amount. The carbonization procedure is more effective at lower temperatures than higher temperatures; thus, the temperature is gradually raised to the desired level at a rate of 20 °C/min. Electron microscopy is used to evaluate the efficiency of pollution removal as well as the physical properties of activated carbon. The electron microscopy technique is critical for determining the efficacy of activated carbon in removing pollutants from a variety of sources. Researchers can gain insights into the mechanisms of pollutant removal and identify areas for improvement by analyzing the microstructure of activated carbon using electron microscopy. Overall, electron microscopy serves as a powerful and valuable technique enabling researchers to delve into the intricate interactions between activated carbon and pollutants, ultimately leading to a deeper comprehension of these processes and facilitating the development of more efficient pollution control measures [32]. Activated carbon is a versatile material with wide-ranging applications due to its high surface area, porosity, and unique surface chemistry [33].

There has been limited research on the use of activated carbon in textiles, but no in-depth studies have been conducted comparing the performance of biomass-based activated carbon filters with those using standard filters. There has been a lack of knowledge on effective application techniques to integrate activated carbon into textile fabrics for particulate matter capture, even though activated carbon is widely used in many applications such as gas masks and air purifiers. Closing this gap will increase the use of activated carbon filters in the textile sector and improve their sustainability and performance. Activated carbon filters can be made more effective, efficient, and sustainable by comparing biomass-based and conventional filters and looking at the application method. Such studies are the subject of this work.

EXPERIMENTAL PART

Materials

Organic waste, wood sawdust and banana peel were obtained from the local market (Pakistan). Phosphoric acid (H3PO4), distilled water and sodium bicarbonate were purchased from Merck, Germany. A hot air furnace (YCO-N01, Gemmy Industrial Corp, Taiwan) was used to obtain activated carbon. The activated carbon produced from organic waste was used to cover a 1′1 inch polyester woven fabric to test filtration efficiency. Polyester (Al-Karam Textile Mills, Pakistan) was selected because it is compatible with the acrylic plush blanket of the Textile Spinning Industry rotary air filter. The characteristics of the polyester fabric used in the prototype are shown in Table 1.

T a b l e 1. Polyester fabric characteristics

Characteristics	Standard	Specifications
Weave design	Industry standard	Plain 1/1
Weight of fabric, g/m^2	ASTM D3776	98.2
Picks per inch (PPI)	ISO 7211-3	88.0
Ends per inch (EPI)	ISO 7211-3	144.0

Preparation of activated carbon

Banana peels

The process of obtaining activated carbon from banana peels is shown in Figure 1a. Banana peels were washed and dried in the sun for 24 h. After drying, 10 g of banana peel samples were burned at a specific carbonization temperature of 200°C in a muffle furnace for 1 h. The obtained charcoal was cooled to room temperature and washed with distilled water to remove dust and impurities. Then, the charcoal was dried in an oven at 105°C for 1 h and crushed into powder with a mortar and pestle. Then, the material was soaked in 4 mL of concentrated phosphoric acid for 24 h to activate the acid, which increased the porosity and surface area of the activated carbon in the adsorption process. After soaking, the material was burned again at the same carbonization temperature and time. Then, the material was soaked in 4 mL of distilled water and 0.04 g of sodium bicarbonate for 24 h to remove excess phosphoric acid. Finally, the material was washed with distilled water to neutral pH and dried in an oven at 110°C for 1 h. The final yield of activated carbon obtained from 10 g of banana peel was 4.64 g. It is worth noting that banana peels are a valuable source of cellulose and hemicellulose, which are key components in the production of activated carbon. Activated carbon derived from banana peels has shown significant potential in eliminating heavy metals from various sources.

Wood sawdust

The organic waste, in this case wood sawdust, as shown in Figure 1b, was first washed and dried in the sun for 24 h. Then, 10 g of wood sawdust samples were burned at a specified carbonization temperature of 280°C in a muffle furnace for 1 h. The resulting charcoal was then cooled to room temperature for 30 min and washed with distilled water to remove dust and impurities. The charcoal was then dried in an oven at 105°C for 1 h and crushed into powder using a mortar and pestle. Then, the material was soaked in 4 mL of concentrated phosphoric acid for 24 h to activate the acid, which increased the porosity and surface area of the activated carbon in the adsorption process. After soaking, the material was re-burned at the same carbonization temperature and time. The material was then soaked in 4 mL of distilled water and 0.04 g of sodium bicarbonate for 24 h to remove excess phosphoric acid. Finally, the material was washed with distilled water until pH neutral and dried in an oven at 110°C for 1 h. The final yield of activated carbon obtained from 10 g of wood sawdust was 0.684 g. It is worth noting that wood sawdust is a by-product of the woodworking industry and is often used as a fuel source. However, it can also be used to produce activated carbon, which has applications in areas such as water treatment, air purification, and energy storage.

Fig. 1. Systematic flow chart of synthesized activated carbon

Methods

Characterization of synthesized activated carbon

FT-IR spectra of the synthesized activated carbon from wood sawdust and banana peels were obtained using Nicolet 5DX FT-IR, USA, using the following parameters: sample scans – 16, background scans – 16, resolution – 8000, sample gain – 1.0 cm^{-1}, optical velocity – 0.4747, aperture – 100.00, wavenumber range 4000-400 cm^{-1}.

The XRD (Xpert PRO, Panalytical Company, Netherlands) analysis was conducted using CuKα radiation with a wavelength of 1.54060 Å. The scan range (2θ) was 10.0125–79.9875°, with a step size of 0.0250° and a scan step time of 0.6 s. The measurements were performed at a temperature of 25°C.

Filtration efficiency

The iodine adsorption test was performed according to the ASTM D4607-14 standard. It is a simple and fast method to estimate the amount of iodine molecules that can be adsorbed on the inner surface of the material, and the degree of this adsorption is proportional to the inner surface of the activated carbon [33, 34], which can be observed from Equations 1–3.

$$N_r = N_1 \frac{V}{50} \tag{1}$$

$$X = (279.246\, N_2\, V) - (12.693\, N_1) \tag{2}$$

$$I = \frac{X}{M} A \tag{3}$$

The moisture content of activated carbon was determined using G209A oven (Atlas SDL, UK) by calculating its water content based (a) on dry bases (b) by exercised the Equation 4.

$$Moisture\ Content = \frac{a-b}{a} \cdot 100\% \tag{4}$$

Microscopic analysis was conducted by stereo type optical microscope (MIDAS, USA). It provides stereoscopic 3D views by using two optical paths. Two objective lenses, positioned at different angles, produce slightly different views. Typically, between 7× and 45×, with higher magnifications available in some models. Transmitted or reflected light, often with adjustable intensity.

Statistical analysis for particulate matter removal efficiency

The statistical analysis was conducted to investigate the significance of saw dust and banana peel carbon filters with polyester filters for the removal of PM_1, $PM_{2.5}$ and $PM_{10.0}$ using Tukey test by using Minitab software (version 17) at a significance level of (α=0.05).

Filter preparation

Activated carbon is screen printed onto synthetic polyester fabric (6×6 inches) with the G3 binder (chemical composition of a styrene-acrylic resin water emulsion – Acryline-RA 50 G3 EX, Ultrus, USA) used as the adhesive material. A layer of activated carbon was applied to the fabric surface during the coating process to improve its adsorption properties and allow for efficient air filtration (Fig. 2). To ensure proper curing and bonding of the activated carbon to the fabric fibers, the screen-printed fabric is allowed to dry in a controlled environment of 90°C and for 30 min. Polyester fabric (98.2 g/m^2) filter samples are prepared by applying three different concentrations of produced activated carbon. The first sample is screen printed with 10% banana peel based activated carbon, the second with 10% wood sawdust based activated carbon, and the third with a mixture of 10% banana peel and 10% wood sawdust based activated carbon mixture.

Wooden filter box

The prototype was constructed by adding slits on the inlet side of the box that allow air to enter and on opposite side a 12 V fan was installed and powered by a chargeable adapter which helps to exhaust the air from the filter prototype (Fig. 3). The filter slider plays a significant role in capturing and removing airborne pollutants. The filter slide is a wooden frame that was specifically designed to hold the filter media, i.e., activated carbon screen printed fabric. To ensure a stable and secure fit, the fabric was attached to the wooden frame using clips. Also, it was strategically placed at the center, to allow optimal airflow through the filtration system. To evaluate the performance of the prototype, a digital anemometer of model number GM816 (Benetech, China) was placed before and after the filter slider. This arrangement enables to record air flow rates and pressure differentials at the respective points. Moreover, the efficiency of the prototype evaluates by placing a particulate matter detector i.e., measured by formaldehyde detector (WP6930S, Ingeres, China) at the outlet, which enable us to record the concentration of particulate matter present in the filtered air.

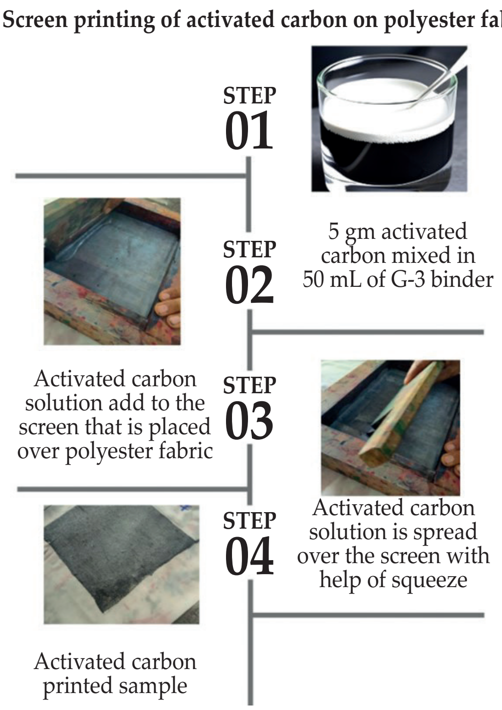

Fig. 2. Screen printing of activated carbon on polyester fabric

Fig. 3. View of the filter box

RESULTS AND DISCUSSION

FT-IR analysis

The FT-IR spectrum of the banana peel-based activated carbon is shown in Figure 4. The spectrum shows several characteristic peaks corresponding to different functional groups present in the sample. The peak at 413 cm^{-1} can be assigned to the bending vibration of C-H bonds in the activated carbon. The peak at 440 cm^{-1} can be assigned to the bending vibration of C-H bonds in the aromatic ring. These peaks indicate the presence of aliphatic and aromatic hydrocarbons. The peak at 1078 cm^{-1} corresponds to the stretching vibration of C-O bonds, indicating the presence of alcohols, ethers, or esters in the activated carbon. The peak at 1605 cm^{-1} corresponds to the stretching vibration of C=C bonds in the aromatic ring, indicating the presence of aromatic compounds in the sample. The peak at 3345 cm^{-1} corresponds to the stretching vibration of O-H bonds in the activated carbon. This peak indicates

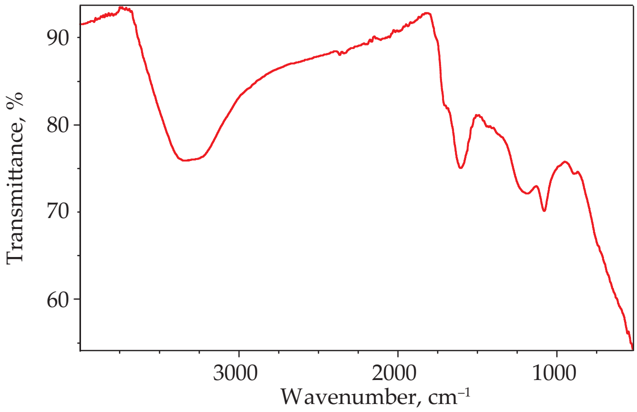

Fig. 4. FT-IR spectrum of activated carbon from banana peels

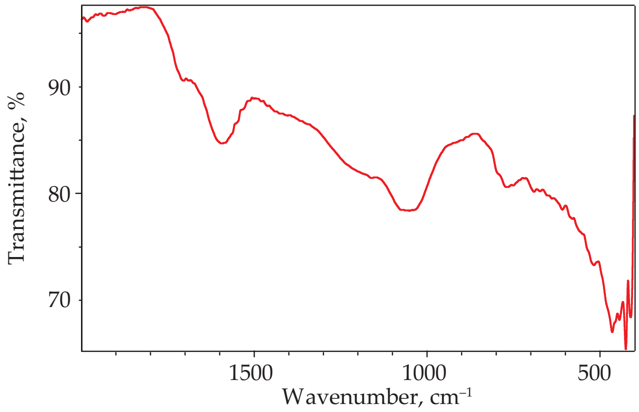

Fig. 5. FT-IR spectrum of activated carbon from wood sawdust

the presence of hydroxyl groups, which are likely to be associated with the formation of oxygen-containing functional groups during the activation process. The FT-IR analysis of activated carbon from banana peel shows the presence of O-H, C-O, C=O, C=C and C-H groups. Several functional groups, such as carboxylic acid, carbon dioxide, and aromatic compounds, were found in activated carbon produced from banana peels, pomegranate, orange peels, and date stones were analyzed using FT-IR [35].

The presence of hydroxyl groups indicates that the activation process introduced oxygen-containing functional groups. Furthermore, the presence of these functional groups suggests that banana peel-based activated carbon may be effective in adsorbing a wide range of pollutants from the air, including both polar and nonpolar compounds. Due to its large surface area and adsorption capacity, activated carbon can be used as an adsorption material to remove pollutants from the air.

The spectrum for the activated carbon from wood sawdust shows several distinct peaks in the region from 4000 to 400 cm^{-1} as shown in Figure 5. The peaks at wavenumbers 411 cm^{-1} and 425 cm^{-1} may indicate the presence of hydroxyl (-OH) or carbonyl (C=O) functional groups. The peak at 464 cm^{-1} may be attributed to the presence of C-H bending vibrations. The peak at 1051 cm^{-1} suggests the presence of more complex functional groups

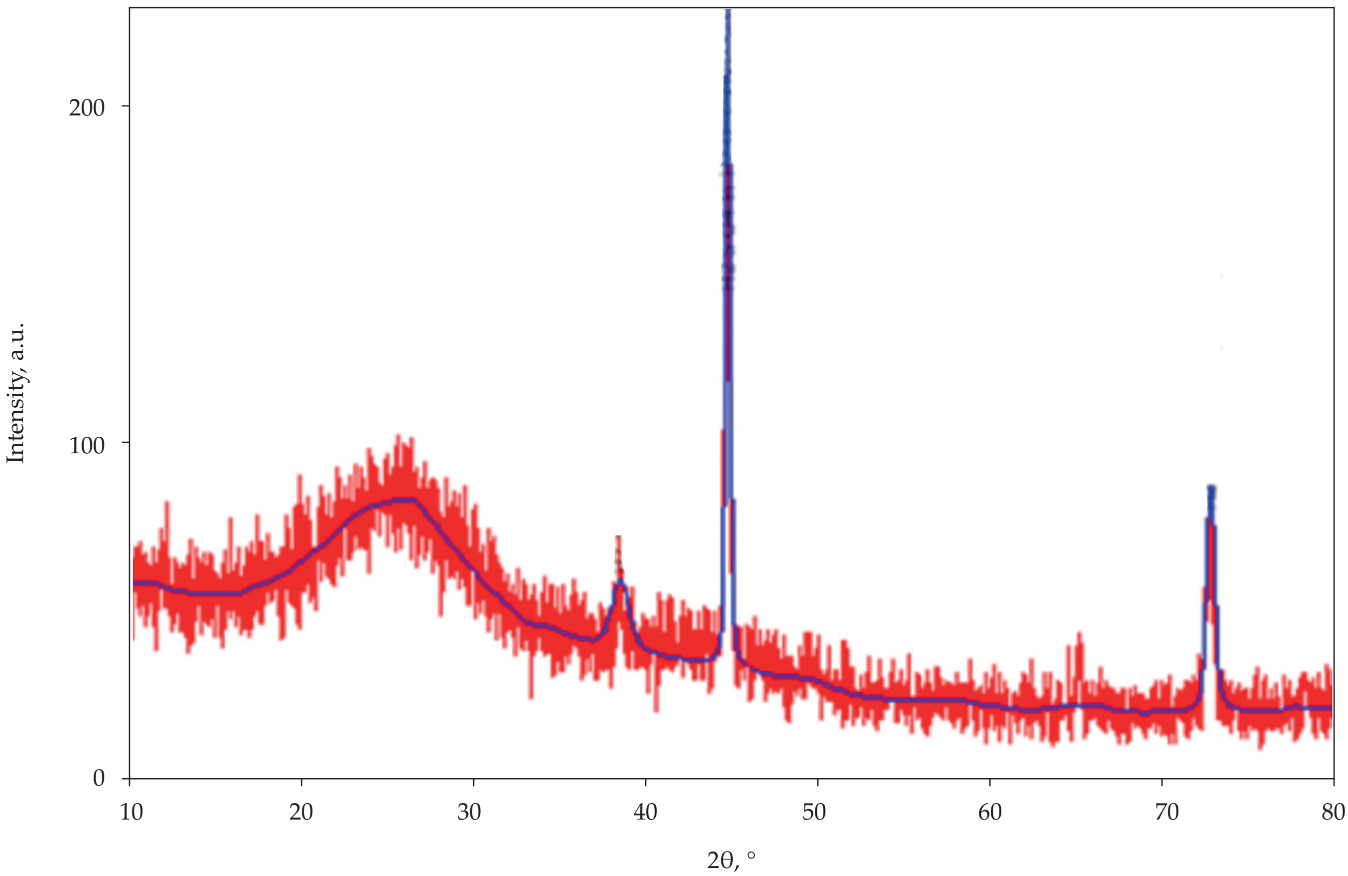

Fig. 6. XRD pattern of activated carbon from banana peels

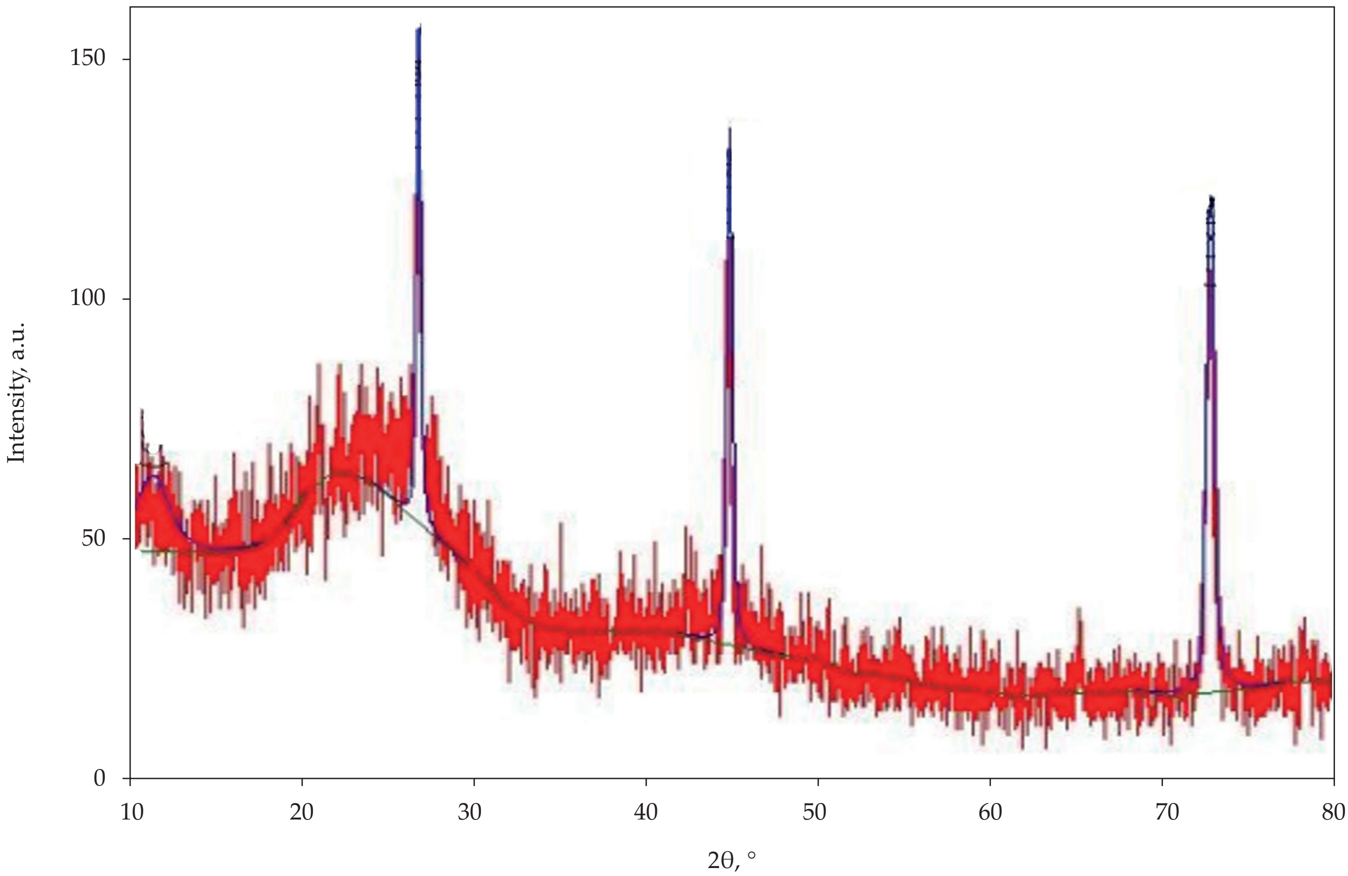

Fig. 7. XRD pattern of activated carbon from wood sawdust

such as phenols or esters. The peak at 1592 cm^{-1} may also indicate the presence of aromatic compounds. The peak with the highest intensity at 3329 cm^{-1} may be attributed to the presence of a functional group such as carboxylic acid (-COOH). Overall, the presence of various functional groups in the wood sawdust based activated carbon suggests that it may be effective in adsorbing a wide range of pollutants from the air, including both polar and non-polar compounds.

A previous study showed in comparison to activated carbon sawdust exhibited the highest adsorption in removal of inorganic pollutants from water. The presence of polyphenolic, carboxylic, and hydroxylic groups contributed to this increased ability [38].

XRD

The XRD analysis of the banana peel activated carbon revealed distinct peaks in the diffraction pattern. Figure 6 shows the peaks at the following 2θ values: 11.20°, 26.68°, 44.76° and 72.68°. These peaks can be assigned to the (100), (002), (101) and (004) planes of the carbon phase, respectively. The XRD pattern of activated carbon from banana peels reveals the presence of well-defined peaks, indicative of a crystalline structure. The pattern was compared with a database of known compounds, and the matches suggested the presence of hydrogen sulfate, carbon nitride and silicon carbide. The XRD results confirm that the sample was composed of carbon.

The XRD pattern of the activated carbon from wood sawdust revealed distinct peaks at 11.19°, 26.68°, 44.76°, and 72.68° (Fig. 7). These peaks correspond to the (100), (002), (101), and (004) planes of the carbon phase, respectively. The results indicate that the sample consists mainly of carbon with a relative intensity of 67%. Other compounds detected include poly(gamma-methyl-L-glutamate) and carbon nitride suggesting that the sample may not be entirely activated carbon, but rather a composite material.

Iodine adsorption

The iodine adsorption test is a simple and fast method used to estimate the internal surface area of activated carbon [33, 34]. The results of examined waste material-derived active carbon are presented in Table 2.

As N_r is 0.0498 N (banana peels) and 0.0366 N (wood sawdust) that are not between 0.008 and 0.0334 N therefore correction factor A is not applied. The iodine adsorption of banana peel based activated carbon is 946.48 mg/g, and wood sawdust based activated carbon is 790.31 mg/g which is in acceptable range i.e., 500–1200 mg/g that is equivalent to surface area of 900–1100 m^2/g.

T a b l e 2. Iodine adsorption data

Waste material	Mass of activated carbon, g	Normality of iodine solution, N_1	Normality of sodium thiosulfate solution, N_2	Volume of sodium thiosulfate solution, ml	N1=N2*V/50, N	X = (279.246 N_2 V) – (12.693 N_1), mg	I=(X/M) *Amg/g
Banana peel	0.733	0.1	0.1	24.9	0.0498	694.05	946.48
Wood sawdust	0.645	0.1	0.1	18.3	0.0366	509.75	790.31

Moisture content

The hygroscopic property of activated carbon was determined by calculating its water content before and after drying using Equation 4. The results of calculations are presented in Table 3. The moisture content of activated carbon from banana peels and wood sawdust is 6.36% and 5.32%, respectively, which is in accordance with the Indonesian Industrial Standard (SII No. 0258-88) in which the maximum allowable moisture content for activated carbon is 15%. The results suggest that both materials have the potential for high adsorption capacity [37, 38].

Prototype wooden air filter

The evaluation of prototype filter was exercised at Amna Industries Ltd, a spinning industry located in Karachi, Pakistan in three phases with help of prototype's efficiency, pressure drop and quality factor [18]. Assessment of the air filter prototype was done with three different phases and polyester fabric filter being used in each phase. In the first phase, the prototype was evaluated with regular polyester fabric, while in the subsequent phases, polyester fabric screen printed with activated carbon derived from banana peel and wood sawdust were utilized.

T a b l e 3. Hygroscopic property of activated carbon

Waste material	Mass of activated carbon before drying, mg	Mass of activated carbon after drying, mg	Moisture content, %
Banana peels	0.645	0.604	6.36
Wood sawdust	0.733	0.694	5.32

Filtration efficiency

As presented in Figure 8, the highest filtration efficiency was observed for $PM_{1.0}$, followed by $PM_{2.5}$, and then $PM_{10.0}$ for all filtrate media. Linear trend line regression analysis shows significant coefficient of determination ($R^2>0.81$), ($R^2>0.94$), ($R^2>0.91$) and ($R^2>0.97$) for unimpregnated polyester filter, banana peels polyester filter, wood sawdust polyester filter and mixture of banana peels and wood sawdust polyester filter, respectively. Among the three-filter medium, banana peels polyester filter shows the highest filter efficiency due to high iodine adsorption magnitude than wood sawdust activated carbon (Table 2).

Pressure drops

From the data presented in Table 4, all air filter prototypes showed similar pressure drops (ΔP) of about 23%,

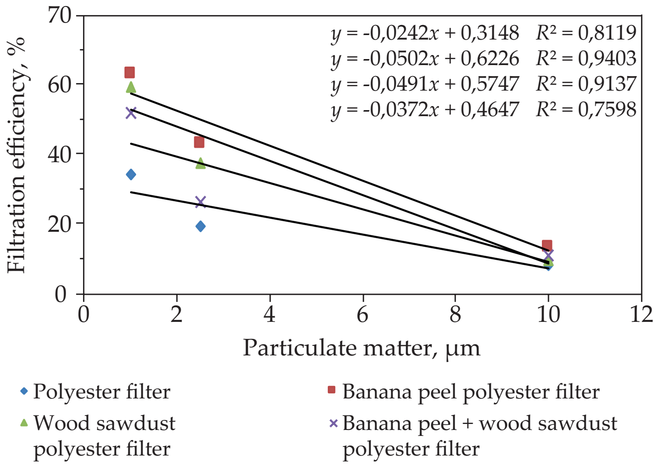

Fig. 8. Filtration efficiency depending on the filter type

T a b l e 4. Pressure drops calculation of prototype air filter

Filter code	Filter media	Air flow speed before filter media, miles/h	Air flow speed after filter media, miles/h	Air pressure before filter media lb./ft²	Air pressure after filter media lb./ft²	ΔP %
PF	polyester	11.1	5.5	0.31	0.077	23.3%
PBF	polyester screen printed with banana peels activated carbon	11.1	5.6	0.31	0.078	23.2%
PWF	polyester screen printed with wood sawdust activated carbon	11.1	5.4	0.31	0.076	23.4%

T a b l e 5. Air filter quality factor analysis

Filter medium	PM	E_{PM}	ΔP %	QF
Polyester filter	$PM_{1.0}$	34%	23.30	1.78
	$PM_{2.5}$	19%	23.30	0.92
	$PM_{10.0}$	8%	23.30	0.003
Polyester screen printed with banana peel activated carbon	$PM_{1.0}$	63%	23.20	4.23
	$PM_{2.5}$	43%	23.20	2.42
	$PM_{10.0}$	13%	23.20	0.60
Polyester screen printed with wood sawdust activated carbon	$PM_{1.0}$	59%	23.40	3.83
	$PM_{2.5}$	37%	23.40	2.00
	$PM_{10.0}$	10%	23.40	0.41

which indicates that the resistance encountered by the air flow speed and air pressure is not affected by the type of activated carbon used. In addition, the filter prototypes maintain low air flow resistance, which indicates the possibility of practical activated carbon use as a sustainable solution in air filtration systems.

Quality factor

The quality factor (QF) is a critical parameter that characterizes the overall performance of air filters and provides information on their efficiency in removing particulate matter and the associated pressure drop across the filter media. Table 5 shows that the overall performance of an air filter depends on the filter efficiency and pressure drop and follows a similar trend in particulate size removal. These results confirm the potential of using activated carbon derived from renewable resources, such as banana peels and wood chips, as effective and sustainable air filtration materials. The combination of economical and environmentally friendly materials in these prototypes offers promising solutions for mitigating air pollution and improving indoor air quality. The use of waste materials, such as banana peels and wood sawdust, in the production of activated carbon further increases the environmental benefits by reducing waste and promoting a circular economy.

Statistical analysis for particulate matter filtration efficiency

The statistical analysis was conducted for particulate matter (PM_1, $PM_{2.5}$ and $PM_{10.0}$) filtration efficiency between polyester filter (×1), polyester screen printed with banana peel based activated carbon (×2) and polyester screen printed with wood sawdust based activated carbon (×3). Table 6, showed that the p-value is highly significant with difference between ×1 and ×2, followed by ×1 and ×3 and then between ×2 and ×3 for $PM_{1.0}$ and $PM_{2.5}$ as compared to carbon filters treatment on $PM_{10.0}$ particulates. The results showed that banana peel carbon filters have more statistical influence on filtration efficiency for $PM_{2.5}$ particulate matter as compared to saw dust carbon filter. Similarly, looking at Tables 6–8, showed that the same pattern of statistical significance with co-relationship between two groups of means having highly significant value with ×1 and ×2.

The statistical analysis of the filtration efficiency of particulate matter ($PM_{1.0}$, $PM_{2.5}$ and $PM_{10.0}$) was carried out for the polyester filter without activated carbon (×1), with activated carbon from banana peels (×2) and with activated carbon from wood sawdust (×3). From Table 6, the p-value is highly significant at the difference of ×1 and ×2, then ×1 and ×3, and then between ×2 and ×3 for $PM_{1.0}$ and $PM_{2.5}$ compared to the carbon filters for the purification of $PM_{10.0}$ particulate matter. Moreover, the banana peels carbon filters have a greater statistical effect on the filtration efficiency of $PM_{2.5}$ compared to the carbon filter from wood sawdust. Similarly, it is clear from Tables 6–8 that the same

T a b l e 6. Statistical analysis of the two group means for $PM_{1.0}$ particulate matter filtration

Pair	Difference	SE	Q	Lower CI	Upper CI	Critical mean	p-value
×1–×2	29	0.5	58	26.0452	31.9548	2.9548	0.000012
×1–×3	20	0.5	40	17.0452	22.9548	2.9548	0.0001525
×2–×3	9	0.5	18	6.0452	11.9548	2.9548	0.002171

T a b l e 7. Statistical analysis of the two group means for $PM_{2.5}$ particulate matter filtration

Pair	Difference	SE	Q	Lower CI	Upper CI	Critical Mean	p-value
×1–×2	24	0.5	48	21.0452	26.9548	2.9548	0.00002523
×1–×3	18	0.5	36	15.0452	20.9548	2.9548	0.000263
×2–×3	6	0.5	12	3.0452	8.9548	2.9548	0.007042

Table 8. Statistical analysis of the two group means for $PM_{10.0}$ particulate matter filtration

Pair	Difference	SE	Q	Lower CI	Upper CI	Critical Mean	p-value
×1–×2	5	0.5	10	2.0452	7.9548	2.9548	0.0119
×1–×3	2	0.5	4	-0.9548	4.9548	2.9548	0.1288
×2–×3	3	0.5	6	0.0452	5.9548	2.9548	0.0481

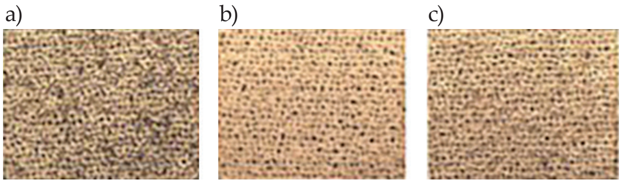

Fig. 9. Optical microscopic images of polyester fabric impregnated with activated carbon derived from: a) banana peels, b) sawdust and c) banana peels/sawdust (10/10); magnification ×15

pattern of statistical significance in the case of correlations between two groups of means holds for ×1 and ×2.

Morphology of activated carbon filters

The surface morphologies shown in Fig. 9 indicate the formation of pores on the surface of the activated carbon filters screen printed on polyester. Due to the increased surface area and higher porosity of the adsorbent, the largest number of particles was deposited on the banana peels carbon filter.

CONCLUSIONS

The results show that screen printing of synthesized activated carbon from banana peels and wood sawdust on polyester fabric significantly improves the filtration efficiency of the prototypes for different sizes of particulate matter ($PM_{1.0}$, $PM_{2.5}$ and $PM_{10.0}$). Enhanced efficiency in air pollutant removal was found, with the filtration efficiency of activated carbon from banana peels reaching as high as 89% for $PM_{1.0}$ compared to 34% without activated carbon. In addition, pressure drop analysis showed that the prototypes maintained low airflow resistance, indicating their suitability for practical application in air filtration systems. Moreover, the calculated quality factor values highlighted the excellent performance of the prototypes in terms of both filtration efficiency and airflow resistance. These results confirm the potential of using activated carbon derived from renewable sources such as banana peels and wood sawdust as effective and sustainable air filtration materials. The combination of economical and environmentally friendly materials in these prototypes offers promising solutions for mitigating air pollution and improving indoor air quality. Using waste materials such as banana peels or wood sawdust in the production of activated carbon contributes to increased environmental benefits by reducing waste and promoting the principles of a circular economy. The results encourage further research and development into the use of biomass-derived activated carbon in sustainable air purification technologies, contributing to a greener and healthier future.

Authors contribution

M.A. – conceptualization, methodology, validation, investigation, writing-original draft, writing-review and editing, visualization; M.A. – methodology, investigation, validation, writing-review and editing.

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Conflict of interest

The authors declare no conflict of interest.

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