

The Adsorptive and Scavenging Properties of Activated Carbon Make it Suitable as a Component of Active Food Packaging Materials

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As sustainability and food safety continue to gain more attention, the demand for environmentally friendly packaging materials has increased significantly. This review emphasizes the transformative potential of activated carbon derived from renewable sources in addressing critical challenges in food packaging. Activated carbon is recognized for its outstanding adsorption capacity, large surface area, and porous structure, which enable it to capture gases such as oxygen, moisture, and ethylene, all of which contribute to food deterioration. In addition to these properties, activated carbon exhibits antimicrobial activity and can facilitate the release of nanoparticles, thereby enhancing food safety through the inhibition of microbial growth. Its multifunctional characteristics make it suitable for various uses, including prolonging shelf life and maintaining the sensory attributes of food products. The local production of activated carbon from agricultural residues supports circular economy practices by reducing reliance on fossil-based resources and minimizing environmental impact. This review highlights the important role of activated carbon in the development of sustainable and multifunctional food packaging technologies that support global initiatives aimed at reducing plastic waste and promoting green innovation.

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INTRODUCTION

The global food packaging industry is undergoing a transformative shift toward sustainability, driven by increasing environmental concerns and the urgent need for food safety assurance. Conventional petroleum-based synthetic plastics, such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS), have long dominated the food packaging industry due to a combination of desirable properties. These materials exhibit excellent mechanical strength, flexibility, thermal stability, moisture and gas barrier performance, and ease of processing, which are critical for preserving food quality, extending shelf life, and supporting high-speed industrial packaging operations (Marsh and Bugusu 2007; Siracusa *et al.* 2008; Geyer *et al.* 2017).

Additionally, their low production costs, chemical resistance, and compatibility with printing and sealing technologies have contributed to their continued widespread use in both rigid and flexible food packaging formats.

Petroleum-based packaging materials pose significant environmental challenges because of their resistance to microbial degradation and their reliance on finite fossil fuel resources (Geyer *et al.* 2017; Singh and Walker 2024). The global recycling rate for plastic remains critically low, with only about 9% of plastic waste successfully recycled—which is far less than the rates for materials such as paper, metals, and glass (Singh and Walker 2024). Despite growing environmental concerns, the functional superiority and infrastructure built around these plastics make it very challenging to dry to replace them with biodegradable alternatives (Han *et al.* 2018).

In regions such as Southeast Asia, particularly within the Association of Southeast Asian Nations (ASEAN) countries, plastic packaging usage is pervasive and contributes substantially to land and marine pollution. If current trends persist, the Centre for International Environmental Law (CIEL) forecasts that by 2050, plastic production alone could account for 13% of the global carbon budget, equivalent to the emissions from approximately 615 coal-fired power plants (CIEL 2019; Sharma *et al.* 2023). Furthermore, global plastic usage is projected to escalate from 464 million tonnes (Mt) in 2020 to 884 Mt by 2050 (Dokl *et al.* 2024). These figures underscore the pressing need for biodegradable and environmentally benign alternatives to plastic food packaging.

One promising avenue for addressing these challenges is the development of bio-based and active food packaging materials. Active food packaging extends beyond the traditional role of serving as a passive barrier; instead, it actively interacts with food or the surrounding environment to prolong shelf life, enhance quality, and ensure safety (Ahvenainen 2003; Yam *et al.* 2005). Such systems incorporate functional agents that absorb or release gases, regulate moisture, and suppress microbial activity, thereby maintaining the integrity of packaged food products.

In parallel with the emergence of active packaging, interest in edible films and coatings has grown significantly. Although these technologies may appear novel, the concept dates back to the 12th century, when wax was applied to fruits in China to reduce moisture loss during storage and transport (Erkmen and Barazi 2018). Modern edible films and coatings are developed using renewable natural polymers such as polysaccharides, proteins, and lipids, which offer both sustainability and biodegradability (Hamed *et al.* 2021; Siracusa *et al.* 2008). These films, typically less than 0.3 mm in thickness, can be consumed alongside the food they protect, enhancing product appearance, maintaining mechanical integrity, and serving as carriers for active compounds (Pavlati and Ors 2009; Petkoska *et al.* 2021).

Recent innovations in functional bio-based packaging have enabled the creation of materials that not only improve food preservation but also address critical quality parameters such as gas and moisture control. Oxygen, for instance, accelerates the oxidative degradation of lipids, pigments, and vitamins, leading to rancidity, discoloration, and nutrient loss (Han 2018; Kong and Singh 2016). Excessive moisture in packaging environments fosters microbial growth and enzymatic activity, while moisture loss can degrade texture and consumer appeal in fresh produce and dry goods alike (Galus and Kadzińska 2015; Kong and Singh 2016).

To manage such vapor-phase components, active packaging technologies now integrate various scavengers and emitters. These include oxygen scavengers, CO₂ absorbers, and ethylene adsorbers, which have shown great potential in extending the

shelf life of perishable products (Arrieta *et al.* 2017; Han *et al.* 2018). Materials such as silica gel, zeolites, chitosan, activated alumina, and especially activated carbon have been incorporated as absorbents to regulate internal atmosphere conditions (Wyrwa and Barska 2017). Among these, activated carbon stands out for its high surface area, porosity, and multifunctionality. It's not only as an adsorbent but also as a carrier for antimicrobial and antioxidant agents (Foo and Hameed 2012; Petkoska *et al.* 2021).

Moreover, the incorporation of nanofillers into bio-based matrices has improved the mechanical strength and barrier properties of packaging materials. These fillers act by increasing the tortuosity of diffusion paths for gases, thereby significantly enhancing the material's capacity to block oxygen and moisture penetration (Arrieta *et al.* 2017).

The integration of edible, biodegradable, and active packaging systems represents a crucial step toward sustainable food preservation. By leveraging renewable biopolymers and incorporating functional components, these next-generation packaging technologies align with global environmental goals and provide innovative solutions to food spoilage, safety, and quality challenges.

Despite the growing body of research on active and bio-based food packaging, limited attention has been given to the multifunctional role of activated carbon (AC), particularly its dual capacity as both a passive adsorbent and an active carrier for antimicrobial and antioxidant agents (Bahrami *et al.* 2020; Chaemsanit *et al.* 2017; Ziani *et al.* 2022). This review addresses that gap by providing a comprehensive overview of the integration of AC in modern active food packaging systems. Specifically, the review highlights AC's effectiveness in vapor-phase molecule scavenging (*e.g.*, oxygen, ethylene, moisture, and odor) (Li *et al.* 2020; Xing *et al.* 2023; Gaikwad *et al.* 2019; Huang *et al.* 2021), its antimicrobial capabilities (Tuan *et al.* 2011; Abushaheen *et al.* 2020), and its synergistic function when combined with additives such as essential oils and metal nanoparticles (Ribeiro-Santos *et al.* 2017; Lakshmi *et al.* 2018). Among the various bio-based functional materials explored for packaging, AC stands out due to its exceptionally high surface area, hierarchical pore structure, chemical tunability, and versatile adsorption and release mechanisms (Foo and Hameed 2012; Wibowo *et al.* 2024). These characteristics make AC not only an efficient gas and moisture scavenger, but also an ideal platform for the controlled release of active compounds (Chaemsanit *et al.* 2017; Ziani *et al.* 2022). In addition, its optionally renewable origin, biodegradability, and compatibility with biopolymer matrices position it as a sustainable and high-performance candidate for next-generation food packaging (Lee *et al.* 2023; Yao *et al.* 2024; Dehmani *et al.* 2022). This review further provides a comparative analysis of AC against other commonly used active materials, outlines methods of incorporation, and discusses recent innovations in the field. The distinctive contribution of this article lies in consolidating current knowledge on the emerging applications of bio-based AC derived from agricultural waste, emphasizing its potential as a multifunctional, sustainable solution in advanced food packaging technologies (Rahmawati *et al.* 2024; Samsudin *et al.* 2019; Ajen *et al.* 2023).

Methodology

This review was conducted through a systematic survey of peer-reviewed articles, technical reports, and academic publications relevant to the application of activated carbon in food packaging systems. Primary databases consulted included Scopus, Web of Science, ScienceDirect, and Google Scholar, covering the period from 2000 to 2024. Keywords such as “activated carbon,” “bio-based food packaging,” “active packaging,”

“vapor-phase scavenging,” “antimicrobial packaging,” and “biodegradable packaging materials” were used in various combinations. Studies selected were primarily limited to those published in English and focused on material properties, functionality, incorporation methods, and sustainability aspects of activated carbon and other common active packaging agents. Review and research articles were prioritized based on relevance, citation count, and recency to ensure inclusion of the most credible and up-to-date findings. This review takes into account several incorporation methods of activated carbon into food packaging, such as blending into biopolymer matrices, surface coating, multilayer embedding, and sachet placement, tailored to different functional and structural packaging needs.

Activated Carbon

Activated carbon (AC), also known as activated charcoal, has a long history dating back to ancient civilizations by Roman and Chinese Empires, where it was first used medicinally and for water purification, and potentially even further. However, despite this long history of charcoal use for purification, it took humans over 3000 years to develop charcoal material tailored for more efficient removal of certain target contaminants (Hagemann *et al.* 2018). By the 20th century, activated carbon became essential in various industries, especially for water and air purification and gas masks during World War I. By the 1950s, activated carbon powder was developed, further expanding its use in environmental protection and industrial applications. Today, activated carbon is one of the most widely used adsorbents due to its high surface area, porosity, and ability to capture a wide range of pollutants and contaminants (Tetteh *et al.* 2024). The structure is made up of carbon atoms arranged in a hexagonal pattern (Fig. 1a), which are connected through covalent bonds to form microcrystalline carbon layers (Fig. 1b). These layers exhibit a non-polar or hydrophobic nature on the surface. Intermolecular bonding between the microcrystalline layers generates interlayer spaces, leading to porosity within the material (Fig. 1c). It is primarily employed in water and air purifications, the recovery of precious metals, and the removal of organic and inorganic contaminants from industrial emissions. Its versatility as an absorbent makes it highly effective in applications such as gas separation, food and beverage processings, and pharmaceutical manufacturing (Biedermann *et al.* 2018; Mitura *et al.* 2021; Sadeghalvad *et al.* 2022).

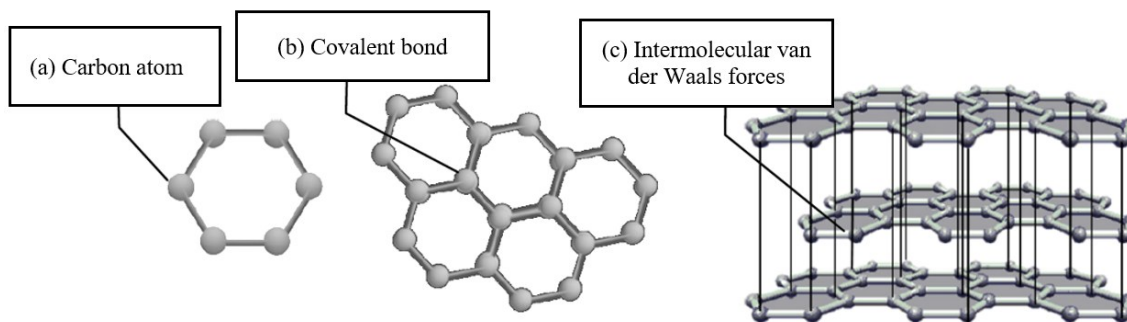


Fig. 1. Structural representation of hexagonal carbon atom (a), microcrystalline carbon layer (b), and activated carbon structure (c); Source: (Chaemsanit *et al.* 2017) Creative Commons Attribution 4.0 International (CC-BY-NC-ND 4.0)

The structure of activated carbon consists of a highly porous, amorphous form of carbon, characterized by its irregular array of slit-shaped pores. This porous structure provides a large surface area, which makes activated carbon highly effective in adsorbing contaminants from gases and liquids, as demonstrated by previous studies (Khezami *et al.* 2005; Boulanger *et al.* 2024). The pores in activated carbon are distributed in different sizes, classified into macropores (>50 nm) to mesopores (2 nm to 50 nm) and micropores (<2 nm), which collectively contribute to its adsorption capabilities (Shiraishi 2014).

Activated carbon is primarily derived from natural raw materials, including renewable and non-renewable resources, as well as agricultural waste. The following table highlights key properties of these sources, which serve as common feedstock for activated carbon production.

Table 1. Source and Properties of Activated Carbon

Source type	Raw material	Key properties of ACs	Reference
Renewable	Wood	High surface area, moderate microporosity, good adsorption capacity	Dehmani <i>et al.</i> 2022
	Coconut husk	High porosity, strong mechanical stability, high iodine number	Tomy <i>et al.</i> 2024
	Bamboo	High surface area, excellent thermal stability, fast adsorption	Yao <i>et al.</i> 2024
	Sugarcane	Good porosity, efficient heavy metal adsorption	Zuo and Liu 2023
	Rice husk	High silica content, good surface area, mesoporous structure	Purwaningsih <i>et al.</i> 2024
	Palm kernel shell	High carbon content, high hardness, effective for gas adsorption	Lee <i>et al.</i> 2023
	Wheat	Moderate porosity, efficient for organic pollutant removal	Koli <i>et al.</i> 2023
Non-renewable resources	Coal	High surface area, predominantly microporous	Fu <i>et al.</i> 2023
	Lignite	Lower surface area, moderate adsorption	Arturi <i>et al.</i> 2023
Agricultural waste	Rice stem	Moderate porosity, good adsorption	Wazir <i>et al.</i> 2023
	Corn residues	Good surface area, balanced micropore/mesopore	He <i>et al.</i> 2023
	Rice straw	High carbon content. Moderate adsorption	Cheng <i>et al.</i> 2024
	Almond shells	High porosity, good structural stability	Aimikhe <i>et al.</i> 2022
	Bagasse	Good adsorption and surface area	Rahmawati <i>et al.</i> 2024

This review emphasizes the potential of renewable resources that garnered significant attention as cost-effective, favorable chemical compositions and high lignin and cellulose content. These characteristics not only enhance their structural integrity and carbon yield during carbonization and activation process making it suitable for adsorption applications such as wastewater treatment, air purification and pollution removal, while also addressing management challenges and contributing to sustainable development (Taha *et al.* 2014; Hanum *et al.* 2017; Arnelli *et al.* 2019; Samsudin *et al.* 2019; Ajien *et al.* 2022). These biomass resources were traditionally utilized for energy production, burned in fields, applied as mulch, or improperly discarded, practices that not only contribute significantly to air pollution and public health risks but also result in the emission of greenhouse gases like carbon dioxide, nitrous oxide, and methane, exacerbating environmental challenges (Lee *et al.* 2023).

Activated carbon derived from biomass waste is abundant and cost-effective, offering a viable option for high-performance coating films, particularly in food packaging. Activated carbon is produced through two main processes: physical activation and chemical activation. In physical activation, gases such as carbon dioxide, air, or steam are used at temperatures ranging from 600 to 900 °C to develop the porous structure. Meanwhile, chemical activation involves impregnating the raw material with chemicals such as phosphoric acid (H₃PO₄), zinc chloride (ZnCl₂), potassium hydroxide (KOH), sodium hydroxide (NaOH), and potassium carbonate (K₂CO₃). These activating reagents break down the structure during subsequent heating, forming highly porous carbon (Burchacka *et al.* 2021; Wu *et al.* 2023; Lionetti *et al.* 2024).

Structural and Physical Characteristic of Activated Carbon

Activated carbon (AC) is characterized by its amorphous carbon structure, typically comprising 85 to 95% carbon by weight, with a high degree of porosity and extensive surface area ranging up to 3000 m²/g (Foo and Hameed 2012; Tetteh *et al.* 2024). It consists of micro-, meso-, and macropores that enable the adsorption of a wide range of molecules through van der Waals forces and electrostatic interactions (Shiraishi 2014; Li *et al.* 2020). The surface chemistry includes functional groups such as hydroxyl, carbonyl, and carboxyl moieties, which influence hydrophilicity, polarity, and adsorption behavior (Luo *et al.* 2022; Wibowo *et al.* 2024). These structural attributes govern its capacity to act as a passive adsorbent and also as a carrier for active compounds in food packaging applications. The high demand for activated carbon has prompted extensive research aimed at developing various types of activated carbon from different materials and methods to suit specific applications, as detailed in Table 2.

Table 2. Classification and Applications of Different Types of Activated Carbon (AC)

Type of activated carbon	Shape/Particle size	Application	References
Powder AC	Between 0.833 and 1.65 mm	Removal of volatile compound,	Tseng 2007
Flute type micropores AC	Symmetric triangle	Lithium-ion batteries	Tian <i>et al.</i> 2017
Granule AC	Irregular shape	Respiratory application	Balanay <i>et al.</i> 2011
Fibre AC	Fiber pleated shaped	Pleated filtering devices	Roegiers and Denys 2021

According to Sosa *et al.* (2023), the utilization of activated carbon across various application areas can be quantified by weight percentage based on literature coverage. The majority of studies focus on its use for the removal of heavy metals (60.0%), followed by dyes (8.5%), organic compounds (7.4%), carbon dioxide (5.8%), ammonia (4.2%), methane (3.7%), hydrogen sulfide (1.3%), and nitrogen dioxide (0.6%). In addition to environmental remediation, activated carbon is also applied in other fields such as catalysis (6.8%), capacitors (1.5%), sensors (0.5%), lithium batteries (0.3%), and pharmaceuticals (0.3%). However, the most critical characteristic of activated carbon that significantly influence its effectiveness in food packaging applications are pore size structure and surface chemistry.

Pore size of activated carbon

The pore size of activated carbon is a critical parameter that must be evaluated prior to its application in adsorption processes. The efficiency of activated carbon in capturing contaminants is greatly influenced by its pore structure, which dictates the surface area available for adsorption and the size of molecules it can accommodate (Wibowo *et al.* 2024). An increased porosity correlates with a larger surface area, thereby enhancing adsorption capacity. This is corroborated by Weldekidan *et al.* (2024), who observed that activated carbon with a significantly high proportion of microporosity exhibited superior carbon dioxide adsorption capacity.

Activated carbon generally presents an irregular morphology, making it challenging to precisely control pore properties such as shape and structure during the activation process (Luo *et al.* 2022; Sagadevan *et al.* 2024). Consequently, the pore size can be adjusted through modifications in the preparation methods to suit the adsorption of various volatile organic compounds (VOCs). Activated carbon's pore structure primarily consists of micropores and mesopores, with a predominant concentration in the micropore range. The mechanism of VOC adsorption on activated carbon with different pore structures is illustrated in Fig. 2.

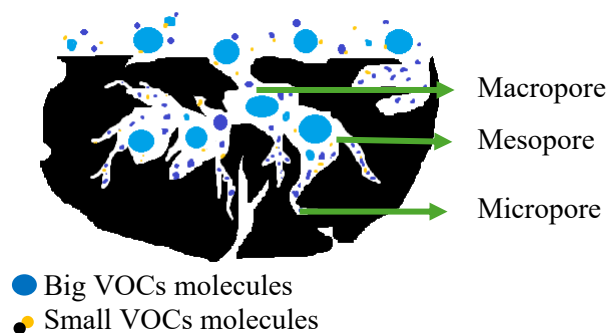


Fig. 2. Pore structure of activated carbon

As noted by Li *et al.* (2020), the pore size distribution significantly impacts the VOC adsorption process. The molecular diameter of VOCs determines which pores are accessible for adsorption. In theory, pores with diameters slightly larger than the molecular diameter of VOC molecules serve as effective adsorption sites. However, if the pore size substantially exceeds the molecular diameter, the adsorption forces between the pore walls and the VOC molecules diminish, reducing the pore's effectiveness to that of a mere conduit. Generally, micropores serve as the primary adsorption sites, while

mesopores facilitate the diffusion of VOCs, thereby enhancing overall adsorption efficiency. Pore size in activated carbon plays a critical role in determining adsorption capacity. Micropores are most effective in adsorbing small molecules due to their high surface area, while mesopores facilitate adsorption *via* both physical interactions and surface adsorption. Macropores primarily act as channels, enabling molecules to move into smaller pores. Misalignment in pore size can lead to lower adsorption efficiency, as each pore type caters to different molecular sizes and adsorption mechanisms.

Potential of Activated Carbon in Food Packaging

Ensuring the safety and quality of food throughout its shelf life is a critical concern in the food industry. A key factor influencing food preservation within packaging systems is the presence of gases such as oxygen, carbon dioxide, moisture, and relative humidity. These environmental factors can accelerate food deterioration, leading to spoilage, nutrient loss, and the growth of harmful microorganisms (Czerwiński *et al.* 2021). To mitigate these issues, it seems that the incorporation of activated carbon into food packaging has gained significant attention as a promising solution.

Due to its well-documented structural properties, activated carbon can play a pivotal role in maintaining the quality of packaged food by adsorbing undesirable gases such as oxygen and moisture (Dastgheib and Karanfil 2004; Chaemsanit *et al.* 2017). This helps create a controlled internal environment that extends shelf life and preserves food integrity. Additionally, activated carbon possesses inherent antimicrobial properties, which contribute to the inhibition of microbial growth, further safeguarding the food from contamination and potential poisoning. Together, these unique attributes position activated carbon as a multifaceted tool in enhancing food packaging systems, ensuring both the safety and longevity of food products.

Comparative properties of activated carbon and other active packaging compounds

To assess the suitability of activated carbon in food packaging applications, it is crucial to compare its properties with those of other commonly used active packaging materials, such as silica gel, clay mineral, zeolites, chitosan and metal oxides. While these materials serve comparable functions, including gas scavenging, antimicrobial activity, and moisture control, they differ significantly in terms of performance environmental impact and cost effectiveness. A detailed comparison of these materials is presented in Table 3.

Table 3. Comparative Properties of Common Materials Used in Active Food Packaging Systems

Material	Primary function	Adsorption capacity	Bio-degradability	Antimicrobial activity	Thermal stability	Cost	References
Activated carbon	Gas scavenger (O ₂ , moisture, VOCs, ethylene)	Very high (up to 3000 m ² /g)	Moderate	Moderate (enhanced with additives)	High	Moderate low	Foo and Hameed 2012; Tetteh <i>et al.</i> 2024
Silica gel	Moisture control	High	Non-biodegradable	None	Moderate	Moderate	Wyrwa and Barska 2017
Natural zeolites	Moisture & gas scavenging	Moderate	Moderate	Weak	High	Low	Bhatia <i>et al.</i> 2022
Chitosan	Antimicrobial agent	Low	Biodegradable	High	Low-moderate	High	Hosseini <i>et al.</i> 2016
Clay mineral	Gas scavenging & odor control	Moderate	Bio-degradable (natural forms)	Weak	High	Low	Aloui and Khwaldia 2016
Zinc oxide	Antimicrobial agent	Low	Non-biodegradable	Very high	High	Moderate	Lakshmi <i>et al.</i> 2018

Among commonly used active packaging materials, activated carbon stands out for its exceptionally high adsorption surface area, broad capacity to trap gases, odors, and moisture, superior thermal stability, and economic scalability. This combination of properties surpasses chitosan and ZnO in adsorption performance, outperforming silica gel and zeolites in multifunctionality, and offering greater versatility when combined with antimicrobial agents such as essential oils or metal nanoparticles.

Incorporation Methods and Additive Synergies of Activated Carbon in Food Packaging

Various techniques have been developed to incorporate activated carbon (AC) into food packaging materials, depending on the intended application and functional requirements. AC can be integrated directly into polymer matrices during extrusion processes, electrospun into nanofibers, laminated as interlayers in multilayer packaging, or applied as surface coatings *via* spraying or casting methods (Youssef *et al.* 2020; Nilsen-Nygaard *et al.* 2021). Another common approach involves enclosing AC in sachets or absorbent pads, which are placed inside the packaging environment for flexible and replaceable use (Gaikwad *et al.* 2019).

The effectiveness of AC in active packaging can be significantly enhanced through the incorporation of functional additives. For example, silver or zinc oxide nanoparticles immobilized onto the AC surface have been shown to improve antimicrobial efficacy against pathogens such as *Escherichia coli* and *Staphylococcus aureus* (Tuan *et al.* 2011; Arakawa *et al.* 2019; Bahrami *et al.* 2020). Similarly, the adsorption of volatile compounds such as ethanol or essential oils onto AC can lead to controlled vapor-phase release, prolonging antimicrobial action and reducing microbial growth on food surfaces (Ribeiro-Santos *et al.* 2017; Chaemsanit *et al.* 2017; Ziani *et al.* 2022). Comparative studies demonstrate that such composite systems exhibit larger inhibition zones and longer-lasting protection than AC alone. These synergistic interactions suggest that AC functions optimally as a delivery matrix and controlled-release platform for active agents, thereby enhancing overall food preservation performance.

The Vapor Phase Molecule Scavenging of Activated Carbon

In the food packaging industry, ensuring the freshness and quality of food products during storage and transportation is paramount. One of the most significant challenges faced by food packaging is the preservation of flavor, aroma, and texture, all of which can be affected by the presence of volatile compounds (Xing *et al.* 2023). These compounds, such as oxygen, moisture, and various odors, can lead to spoilage and degrade the sensory qualities of food. To address this issue, vapor phase molecule scavenging has emerged as an effective solution, particularly through the use of activated carbon.

Activated carbon, owing to its defined porous architecture and high surface area, is ideal for removing unwanted vapor-phase molecules from the surrounding environment. According to Li *et al.* (2020), its ability to trap volatile organic compounds (VOCs), moisture, and odors in packaging systems has positioned it as a valuable component in modern food packaging. The incorporation of activated carbon into food packaging materials provides an efficient method to extend shelf life, maintain product freshness, and protect against contamination from harmful gases and odors. By selectively adsorbing these vapor-phase molecules, activated carbon helps to create an optimized microenvironment within the packaging, thereby slowing down the degradation processes that typically lead to food spoilage (Qu *et al.* 2020).

Oxygen absorption property of activated carbon

In the food packaging industry, maintaining the freshness and quality of products is a critical challenge. There are currently used for items sensitive to oxidation such as meat packaging, bakery products, juice packaging, and milk products. Oxygen, even in small amounts, can lead to spoilage, colour changes, nutrient degradation, and the development of off-flavours in packaged foods (Cichello 2015). The presence of oxygen inside packaging can lead to several undesirable effects as shown in Table 4.

Table 4. Key Factor of Food Quality that is Affected by Oxygen

Effects	Description	References
Oxidative rancidity	Fats and oils in meat can react with oxygen, leading to rancidity, which negatively affects taste and smell.	Wood <i>et al.</i> 2004
Nutrient loss	Oxygen exposure can degrade sensitive vitamin levels.	Cichello 2015
Microbial growth	Aerobic bacteria, molds and yeasts thrive in the presence of oxygen, potentially causing spoilage.	Couvert <i>et al.</i> 2023; Comi and Lacumin 2025
Colour and flavor changes	Oxygen can cause colour fading in products like meat and cut fruits and can alter natural flavors.	Fan <i>et al.</i> 2024; He <i>et al.</i> 2024

Usually, commercial oxygen absorbers are based on oxidation reaction of the chemicals such as iron powder bases or ascorbic acid bases, or enzyme reactions, such as glucose oxidase/catalase bases, which can absorb and reduce oxygen to less than 0.01% (Chaemsanit *et al.* 2017). These chemicals when mixed with activated carbon (charcoal) are proven quite effective (Gupta 2023).

Activated carbon adsorbs oxygen through a physical process driven by Van der Waals forces, which attract oxygen to the surface and into pores of the activated carbon (Wang *et al.* 2020). Tan *et al.* (2017) noted that activated carbon that have undergone thermal treatments or modifications to reduce the hydroxyl and carbonyl groups tend to

exhibit increased hydrophobicity, thereby enhancing their adsorption capacity for nonpolar organic compounds, as shown in Fig. 3.

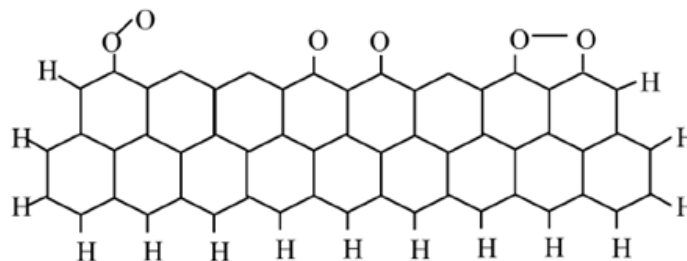


Fig. 3. Different forms of oxygen adsorption at the edge of the activated carbon layer
Source: (Chaemsanit *et al.* 2017) Creative Commons Attribution 4.0 International (CC-BY-NC-ND 4.0)

Adsorption of ethylene by activated carbon

Ethylene (C_2H_4) is a naturally occurring gaseous plant hormone that plays a critical role in the ripening and decay of horticultural products such as fruits and vegetables (Gaikwad *et al.* 2019). While ethylene is essential for the development of many plant processes, its presence in packaging environments can accelerate the ripening, spoilage, and degradation of perishable foods. This can lead to a reduced shelf life and compromised quality. Current commercial practice for removing the ethylene is by using potassium permanganate ($KMnO_4$). It was prepared in the form of sachets and films for placement inside packages, storage facilities, and transportation vehicles to remove fruits and vegetables (Awalgaonkar *et al.* 2020). According to the cited authors, $KMnO_4$ is highly effective at removing ethylene compared to other removers such as sodium permanganate, titanium dioxide, zeolite, clay, and metal-organic framework. However, $KMnO_4$ has many drawbacks such as being rapidly consumed (needs frequent replacement), needing an inert carrier, having a caustic nature, and not being approved as food contact substance by Food and Drug Administration (FDA) in United States.

To overcome this issue, activated carbon can be used in food packaging as an alternative for food preservatives. It's safe to use and effective in preserving the quality of food products for customers; it also can save costs for food retailers and food industries. Thus, controlling ethylene levels in the packaging can help extend the shelf life of fresh and other ethylene sensitive foods. Gaikwad *et al.* (2019) reported that granular activated carbon exhibited superior ethylene adsorption capacity compared to its powdered and fibrous counterparts. Furthermore, the findings demonstrated that granular activated carbon effectively delayed changes in color, firmness, and weight of tomato fruits while significantly reducing ethylene levels within the packaging for up to 14 days. However, research on the ethylene scavenging capacity of activated carbon remains limited.

Adsorption of water vapor by activated carbon

Among its many applications, the adsorption of water vapor is particularly significant in fields such as air purification, dehumidification, and industrial gas drying. The ability of activated carbon to absorb water vapor is primarily influenced by its pore structure, surface chemistry, and operating conditions, making it a versatile solution for moisture control (Huang *et al.* 2021). The adsorption process involves the physical adherence of water vapor molecules onto the surfaces of activated carbon, driven by Van

der Waals forces and capillary condensation in micropores. Factors such as pore size distribution, surface functional groups, and activation methods play critical roles in determining its efficiency. Moreover, the thermal regeneration of activated carbon, allowing repeated use, enhances its economic and environmental viability (Zanella *et al.* 2014). Activated carbon can maintain effective adsorption performance even in humid environments, owing to its hygroscopic properties and mesoporous structures. When the pressure continues to increase, water molecules begin to fill the micropores on the activated carbon until saturated pressure is reached. Pore filling in activated carbon starts from the smaller pores and later can involve the larger pores at higher relative humidity (Liu *et al.* 2017). Sun *et al.* (2019) demonstrated that water adsorption is significantly influenced by activation temperature, with higher temperatures correlating to enhanced adsorption capacity. This potential renders it highly suitable for applications in selective absorption, particularly in food packaging (Yang *et al.* 2024).

Adsorption of odor by activated carbon

The sorption of odor by activated carbon is a critical process utilized in various applications, including air purification, industrial emissions control, and food packaging. Activated carbon, with its high surface area, microporous structure, and strong adsorption capabilities, effectively removes odor-causing molecules and volatile organic compounds (VOCs) from gases and liquids through a sorption mechanism involving Van der Waals forces and pore filling, while factors such as pore size distribution, surface chemistry, temperature, and humidity further influence its adsorption efficiency (Liu *et al.* 2017; Huang *et al.* 2020). Such attributes contribute to the fact that activated carbon is an essential material in both commercial and environmental applications, where odor control is paramount for maintaining air quality and product integrity. Besides, activated carbon, as non-polar material, demonstrates higher adsorption capacity for non-polar compounds such as carbon disulfide, carbon dioxide, toluene, benzene, phenol, *etc.* Guo *et al.* (2024) found that micropores smaller than 0.71 nm predominantly influence carbon disulfide adsorption, while micropores smaller than 2 nm significantly impact toluene adsorption.

Activated Carbon for Antimicrobial Food Preservation

Activated carbon (AC) plays a complementary and multifunctional role in active food packaging systems, not only as an adsorbent but also as a carrier and controlled-release platform for functional additives such as nanoparticles, antioxidants, and volatile antimicrobials. While AC inherently possesses a high surface area and well-developed porosity, which confer excellent adsorption capabilities, many of its functional properties such as antimicrobial and antioxidant effects are significantly enhanced when used in combination with active agents (Ribeiro-Santos *et al.* 2017; Bahrami *et al.* 2020). The incorporation of metal nanoparticles, such as silver or zinc oxide, onto the AC surface has been shown to impart strong antimicrobial activity through direct surface contact with pathogens (Tuan *et al.* 2011; Bahrami *et al.* 2020). Simultaneously, volatile antimicrobial compounds such as ethanol or essential oils can be adsorbed onto AC and gradually released *via* volatilization, diffusing into the packaging environment to inhibit microbial growth in the vapor phase (Chaemsanit *et al.* 2017; Ziani *et al.* 2022). These combined systems leverage the porous network of AC to facilitate both the adsorption and sustained release of active compounds, thereby enhancing their stability, prolonging their functional activity, and ensuring broad-spectrum food protection. Thus, AC acts

synergistically with these additives, serving as an effective delivery matrix in active food packaging applications.

Adsorption of volatile organic compounds by activated carbon

Among the general antimicrobial substance that are used worldwide, ethanol and essential oil are known as volatile organic compounds that have antimicrobial ability and have been applied in many foods, for example, in ethanol pads, seen mostly in bakery packaging, and as an essential oil coating on many types of fruit (Ribeiro-Santos *et al.* 2017). As demonstrated by Chaemsanit *et al.* (2017), activated carbon has the ability to adsorb ethanol easily and then to release it in vapor form at room temperature. Similarly, essential oils can also be adsorbed by activated carbon and subsequently released. Ziani *et al.* (2022), reported that antimicrobial activity of 20% ethanol extract in water concentration was effective against the bacteria *Escherichia coli* (gram-negative), *Listeria innocua* (gram-positive), *Geotrichum* sp., and *Rhodotorula glutinis*. Essential oil vapor is also among the promising alternative methods to control food spoilage. Such effects can be attributed to their activities in the vapor phase. Their ability to suppress growth of microorganisms in real foods and technology of application, and their use in particular food (because of their strong odors) was studied by Klouček *et al.* (2012). Findings revealed that out of sixty-nine essential oil vapors tested, no microbial growth was observed in any case throughout the experiment, and no “inhibition zones” were detected. Another study reported by López *et al.* (2005) highlighted the vapor approach of essential oils as a promising control method. This technique could be integrated into active packaging to create an environment that minimizes organoleptic alterations in packaged food products.

In addition to its high adsorption, activated carbon also functions as a controlled-release medium, allowing the gradual desorption of adsorbed compounds such as ethanol, essential oils, and nanoparticles under specific conditions. The release mechanism primarily involves physical desorption, which is influenced by external factors such as temperature, humidity, and vapor pressure gradients between the activated carbon surface and the surrounding environment (Chaemsanit *et al.* 2017; Sun *et al.* 2019). For volatile compounds such as ethanol, desorption can occur at ambient temperatures through vapor-phase diffusion with studies showing that up to 98% of adsorbed ethanol can be released at room temperature (Chaemsanit *et al.* 2017). In the case of essential oil, the release is similarly governed by their vapor pressure and molecular interaction with pore surfaces and often enhancing antimicrobial effects within the packaging headspace (Klouček *et al.* 2012; Ribeiro-Santos *et al.* 2017). Surface chemistry, including the presence of functional groups such as hydroxyl and carbonyl groups, also plays a crucial in modulating the interaction strength between the adsorbate and the activated carbon, thereby affecting the desorption rate (Tan *et al.* 2017; Wang *et al.* 2020). Moreover, the pore size distribution significantly determines the retention and release kinetics of the compounds with micropores typically provide stronger adsorption sites, while mesopores facilitate easier diffusion and release (Li *et al.* 2020; Huang *et al.* 2021). This dual functionality of activated carbon (as both an adsorbent and release system) enhances its applicability in active food packaging by enabling the controlled delivery of functional agents while simultaneously scavenging undesirable vapors.

Antimicrobial activity by activated carbon

There are many metal and non-metal nanoparticles that have biocidal properties. These include copper, gold, silver, silica, zinc oxide, and carbon-based nanomaterials. Nanoparticles range in size between 1.0 nm and 100 nm and are currently being used in various areas such as the food industry (Ribeiro-Santos *et al.* 2017). Nanoparticles have created excitement due to their unique physico-chemical properties, especially for antimicrobial products (Lakshmi *et al.* 2018). Among these nanoparticles, silver nanoparticles are widely used due to their antibacterial properties, unique optical characteristics, and high surface area, making them highly reactive. These attributes, combined with the structural support offered by AC, have made silver nanoparticles a focal point of antimicrobial research. Tuan *et al.* (2011) demonstrated that activated carbon that activated carbon infused with silver nanoparticles exhibited significantly stronger against the growth of *E. coli* compared to activated carbon alone.

Table 5. Antimicrobial Activity of Activated Carbon with Metal Nanoparticles

Source of Activated Carbon	Activation Agent	Metal Nanoparticle	Inhibited Micro-organism	Reference
Coconut husk	Physical activation	Silver nanoparticles	<i>E.coli</i>	Tuan <i>et al.</i> 2011
Activated carbon fibre	-	Silver nanoparticles	<i>E.coli</i>	Jiang <i>et al.</i> 2021
Oil palm shells	Physical activation	Silver and copper metallic nanoparticles	<i>E.coli</i>	Arakawa <i>et al.</i> 2019
Water hyacinth	Chemical activation	Zinc oxide nanoparticles	<i>Bacillus subtilis</i> , <i>Staphylococcus aureus</i> , <i>Klebsiella pneumonia</i> , <i>E.coli</i>	Hassan <i>et al.</i> 2022)

Numerous nanomaterials have been explored to investigate the antimicrobial activity of activated carbon coated with various nanoparticles, as presented in Table 5. The results demonstrated that activated carbon effectively released nanoparticles, exhibiting antimicrobial activity against various microorganisms. This activity was observed across different forms of activated carbon, including granular activated carbon, powdered activated carbon, and activated carbon fibers.

Future Directions

This review has explored the potential application of activated carbon in food packaging, drawing insights from various published sources. Activated carbon offers several advantages: It is durable, possesses high mechanical strength and is renowned for its exceptional adsorption capacity. Made optionally from renewable resources, it is natural, eco-friendly, reusable, and cost-effective. Moreover, it can be locally produced using waste organic materials. When pure, it is generally non-toxic, edible, odorless, and multifunctional. In food packaging applications, activated carbon can release adsorbed antimicrobial agents into the packaging environment to inhibit the growth of pathogenic or spoilage bacteria. After releasing these agents, the free carbon atoms on its surface can adsorb gaseous molecules such as oxygen, water vapor, ethylene, or odors, the factors that significantly influence food quality and safety. These processes occur through the inherent properties of activated carbon alone, ensuring efficient control of food quality and safety. Utilizing activated carbon not only enhances food preservation but also promotes sustainability by enabling local production, which supports local industries and

economies. This approach represents a practical and eco-friendly solution for improving food packaging while fostering sustainable development.

CONCLUSIONS

This review has highlighted the transformative potential of activated carbon, specifically derived from renewable resources and used in food packaging applications. As an eco-friendly, cost-effective, and multifunctional material, activated carbon addresses critical challenges in food preservation by extending shelf life, maintaining quality, and enhancing safety. Its exceptional adsorption capabilities allow for the efficient capture of gases such as oxygen, moisture, and ethylene, which play significant roles in food spoilage. Furthermore, the incorporation of antimicrobial agents and nanoparticles expands its utility in inhibiting microbial growth and safeguarding food integrity. By leveraging the properties of activated carbon, industries can simultaneously improve food packaging performance and contribute to environmental sustainability. The ability to produce activated carbon locally from waste organic materials supports circular economy practices, reduces dependency on non-renewable resources, and minimizes environmental pollution. These advantages position activated carbon as a promising material in developing innovative, sustainable food packaging solutions that align with global efforts to promote green technologies and reduce plastic waste.

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