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Ethylene scavengers for extended freshness: A critical comparison between physisorption and chemistry process

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ABSTRACT

This review highlights advancements in ethylene removal technologies tailored for fruit and vegetable (F&V) preservation, with a focus on physical adsorption and chemical elimination methods. Conventional approaches, such as potassium permanganate ($KMnO_4$) and 1-methylcyclopropene (1-MCP), are limited by toxicity concerns, declining efficiency, and potential fruit disorders. Emerging alternatives, particularly catalytic oxidation using metal oxide catalysts like TiO_2, offer efficient ethylene degradation into non-toxic byproducts. Incorporating these catalysts with porous materials, such as zeolites, enhances ethylene adsorption while providing multi-functional benefits, including antibacterial activity. In addition to discussing the materials of the adsorbents, their binding mechanisms (such as van der Waals forces and π-complexation) were also studied. Future research directions include improving cost-efficiency, optimizing material performance for practical applications, and ensuring food safety in packaging systems. These advancements represent a sustainable strategy to extend the shelf life of F&V in the postharvest supply chain.

1. Introduction

As global living standards continue to rise, the demand for diverse and year-round availability of fruits and vegetables has grown substantially. However, the highly perishable nature of these products, primarily due to microbial contamination, contributes significantly to global food losses, with nearly 50 % of such losses attributed to fruit and vegetable spoilage annually (Blanke, 2014; Alegbeleye et al., 2022). A primary factor behind this spoilage is ethylene, a plant hormone that accelerates deterioration during storage and transportation (Patdhanagul et al., 2010). Ethylene triggers both physical and chemical changes (Sue-aok et al., 2010), such as alterations in appearance, texture, and nutritional quality (Liu et al., 2020), leading to increased respiration rates, ripening, softening, senescence, and decay (Wei et al., 2021).

The sensitivity to ethylene varies widely among different fruits, vegetables, and flowers, as summarized in Table 1. The ethylene dose-response curve exhibits a threshold at 0.01 ppm, with half-maximal and maximal effects occurring at 0.1 ppm and 1–10 ppm, respectively. This characteristic supports optimized post-harvest management strategies. Even trace concentrations of ethylene, especially under low-temperature conditions, can initiate overripening and senescence, resulting in postharvest losses as high as 80 % in certain cases (Keller et al., 2013). Consequently, effective strategies to mitigate ethylene production and action during storage are essential to preserving freshness, extending shelf life, reducing food waste, and ensuring food security (Hu et al., 2019; Zhang et al., 2017; Singh et al., 2024). Addressing these challenges demands innovative approaches and technologies that can regulate ethylene levels and improve the sustainability of the global food supply chain.

Ethylene, an essential primary chemical material, dominates>75 % of global petrochemical production (Qian et al., 2023), meanwhile, ethylene, a critical ripening regulator in horticultural produce, originates from endogenous biosynthesis and exogenous environmental sources. Endogenous ethylene is synthesized via enzymatic pathways (1-aminocyclopropane-1-carboxylic acid pathway), whereas exogenous ethylene originates from external factors including microbial activity, organic decomposition, combustion emissions, and plastic photodegradation (Martínez-Romero et al., 2007; Saltveit, 1999). Ethylene control strategies for postharvest management comprise inhibition and elimination approaches. Inhibition strategies employ competitive receptor binding (e.g., 1-methylcyclopropene) to block ethylene signaling

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Table 1
Ethylene Production Rates, Sensitivity Levels, and Principal Effects for Some Fresh Commodities (Keller et al., 2013).

fresh produce type	ethylene production rate (μLkg^{-1} h^{-1})	ethylene sensitivity[a]	principal reaction to ethylene
cherries	very low <0.1	L	softening
potatoes	very low <0.1	M	sprouting
cut flowers	very low <0.1	H	sleepiness, leaf curl
cucumber	low 0.1 – 1.0	H	yellowing
kiwi fruit		H	decay
banana	moderate 1.0 – 10	H	decay
tomato	moderate 1.0 – 10	H	shrink, decay
apricot, avocado	high 10–100	H	decay
apple	very high >100	H	scald, lose crunch
passion fruit	very high >100	H	decay

[a] Ethylene sensitivity (ppm): *H* = high (0.01 – 0.5); *M* = moderate (0.5 – 3); *L* = low (3 – 5).

and delay ripening (Mattheis, 1999). Elimination methods include: Physisorption via microporous adsorbents (e.g., activated carbon, zeolites) for ethylene sequestration (H. Yang et al., 2018b; Erdoğan et al., 2008); Oxidative degradation through either direct chemical oxidizers or catalytic systems. Emerging catalytic oxidation techniques—photocatalysis, thermal catalysis, and plasma catalysis—demonstrate superior efficiency in converting ethylene to CO_2/H_2O under mild conditions, offering sustainable solutions for storage environments.

This review distinguishes itself from previous works by systematically comparing physical adsorption and chemical elimination technologies, with a focus on the potential of emerging catalytic oxidation methods. A clear classification into traditional and emerging approaches is established, along with a critical analysis of their respective advantages and limitations. The study identifies hybrid systems (e.g., metal oxide/nano-molecular sieve composites) as a promising solution to overcome the drawbacks of conventional methods. Importantly, it highlights the need to balance catalytic efficiency with food safety regulations in practical applications. These insights provide researchers with optimization strategies, offer industry practitioners a reference for selecting efficient and safe technologies, and guide technological advancements in post-harvest supply chain management.

2. Ethylene removal methods

To Effective removal or inhibition of ethylene is crucial for preserving fruits and vegetables (F&V) during storage and transportation. Understanding the underlying mechanisms of ethylene synthesis and its role in F&V physiology is essential for designing efficient removal strategies. Fig. 1 illustrates the process of endogenous ethylene synthesis, where the cyclopropane ring is converted into 1-aminocyclopropane-1-carboxylate (ACC), a critical intermediate in ethylene biosynthesis. ACC is subsequently oxidized by the enzyme ACC oxidase, resulting in the formation of ethylene.

The preservation of F&V can be achieved through four primary mechanisms:

(1) **Inhibition of the maturation process**: Experimental data from tomato studies demonstrated that ethylene levels exceeding 0.01 μL/L significantly increase the respiration rate of F&V (Hayama et al., 2006; Ozdemir & Floros, 2004; Mustapha & Zhou, 2021), accelerating chlorophyll degradation, nutrient depletion, and senescence, thereby reducing shelf life.
(2) **Inhibition of bacterial growth**: Controlling microbial contamination is essential for extending F&V shelf life and ensuring food safety.
(3) **Modified Atmosphere Packaging (MAP):** By altering the atmospheric composition—typically reducing O_2 and increasing CO_2 levels—MAP slows the respiration rate and mitigates the ripening effects of ethylene and other aging hormones. This approach helps preserve nutritional quality and prolong shelf life.
(4) **Anti-fogging measures:** Water vapor condensation on packaging films can obstruct visibility and create conditions conducive to bacterial growth. The use of anti-fogging agents prevents droplet formation on film surfaces, maintaining packaging integrity and improving food safety.

Ethylene scavengers are designed to regulate ethylene levels through inhibition, adsorption, and oxidation mechanisms. These include:

(i) **Ethylene inhibitors:** Compounds such as 1-methylcyclopropene (1-MCP) bind to ethylene receptors, effectively blocking its biological activity and delaying ripening.
(ii) **Adsorbents:** Materials like zeolites physically adsorb ethylene, reducing its concentration in the storage environment.
(iii) **Catalytic oxidizers:** Substances such as potassium permanganate ($KMnO_4$), ozone, and titanium dioxide (TiO_2) chemically degrade ethylene into non-toxic byproducts.

Table 2 provides an overview of various ethylene scavengers and their applications in F&V preservation. These methods play a vital role in minimizing postharvest losses and maintaining the quality of produce throughout the supply chain.

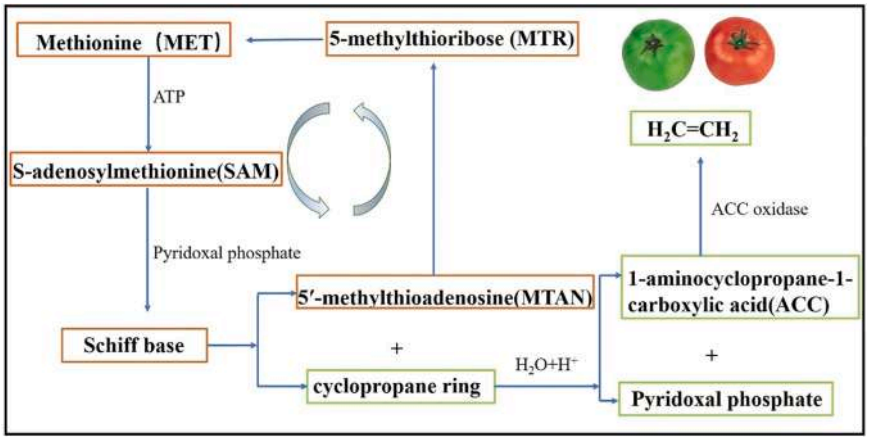


Fig. 1. Mechanism for the biosynthesis of ethylene from methionine (MET).
(Adapted from Ref.(Wei et al., 2021) Copyright 2020 Elsevier)

Table 2
Some applications of ethylene scavengers in fruit and vegetable preservation.

Methods	Applications	Storage conditions	Advantages	Ref.
1-MCP	Tomato	10 °C, 7 days 20 °C, 4 days	Reduced ethylene production and respiration rate	(Guillén et al., 2007)
1-MCP	Avocado	20 °C, 18 days	Delayed accumulation of total soluble phenolics, flavonoids and total antioxidant capacity	(Zhang et al., 2013)
1-MCP	Pear	4 months	Inhibition of polyphenol oxidase gene expression	(Giné-Bordonaba et al., 2020)
1-MCP	Kiwifruit	4 ± 1 °C, 20 days	Improving kiwifruit post-harvest quality and extending kiwifruit shelf life	(Xu et al., 2019)
1-MCP	Apple	2 °C, 14 days	Suppression of internal ethylene concentration in fruits (IEC)	(Watkins & Nock, 2012)
$KMnO_4$	Peach	0 °C, 36 days	Reduces hardness, delays pH increase and maintains good appearance	(Emadpour et al., 2015)
$KMnO_4$	Avocado	–	Near-zero ethylene concentration for >5 days	(Tirgar et al., 2018)
$KMnO_4$	Apple	0 °C, 5 months	Delayed loss of pulp firmness	(Sardabi et al., 2014)
TiO_2/SiO_2	Tomato	15 °C	Extending the quality of fresh fruits and vegetables without unduly increasing costs	(Hussain et al., 2010)
Pt-SBA-15	–	0 °C	SBA-15 loaded Pt catalyst (1.8wt % Pt loading) achieved higher than 99 % ethylene conversion in the initial stage	(S.S. Satter, Yokoya et al., 2018)
0.75 %GO/TiO_2/Bi_2WO_6	–	20 ± 2 °C	High catalytic activity and reusable	(Lv et al., 2019)
Pt-MCM-41	–	0 °C	Conversion of 50 ppm ethylene to 1wt % Pt/MCM-41 at 0 °C exceeds 99.8 %	(Jiang et al., 2013)

2.1. Physical adsorption

The effectiveness of ethylene control methods depends significantly on the storage environment and the specific requirements of the fresh produce being preserved. In modified atmosphere packaging, materials such as ethylene adsorbent pouches, sheets, and liners are widely employed to manage ethylene concentrations. Ethylene removal in these systems is primarily achieved through two mechanisms: oxidation and adsorption (Zhang et al., 2017; Regadera-Macías et al., 2023).

Oxidation-based approaches gradually lower ethylene levels but are often constrained by the limited lifespan of the oxidizing agents, which degrade over time. This reduction in efficiency can compromise the quality and shelf life of fresh produce, particularly during extended storage periods (Kim et al., 2019). Furthermore, oxidation methods frequently necessitate specialized equipment, which can increase operational costs and reduce their applicability in cost-sensitive and small-scale storage scenarios (Sousa et al., 2020).

Conversely, adsorption techniques provide a more economical and sustainable solution for ethylene removal. Materials with high porosity and extensive surface areas, such as activated carbon and molecular sieves, exhibit exceptional capacity for ethylene capture (Erdoğan et al., 2008; Lim et al., 2020; Xiao et al., 2024). These adsorbents leverage physical adsorption mechanisms to sequester ethylene molecules effectively, making them highly suitable for integration into fresh produce packaging systems.

However, the primary limitation of adsorption-based systems is the saturation of the adsorbent material over time. As the adsorbents reach their maximum capacity, their ability to capture ethylene diminishes, necessitating either replacement or regeneration to maintain performance. Despite this challenge, adsorption remains a preferred strategy for ethylene management due to its affordability, ease of implementation, and versatility across a broad range of storage applications.

2.1.1. Activated carbon (AC)

Activated carbon (AC) is a highly porous material with a small pore size and low volume, making it highly effective for adsorption and chemical reactions. Its well-developed pore structure, large specific surface area, low density, and chemical resistance make it widely applicable in both liquid-phase and gas-phase adsorption, often in the form of particles or powders (Liang et al., 2017; Skouteris et al., 2015). These advantageous properties have made AC a popular choice for ethylene removal applications.

The efficiency of physical adsorption by AC is influenced by its pore structure and surface properties, including pore size distribution, specific surface area, and surface chemistry. These characteristics can be tailored through activation or functionalization processes, enabling the development of materials with enhanced adsorption capacity. For example, carbon dry gels, first synthesized by Pekala et al. in the early 1990s using a sol-gel process, have demonstrated excellent tunability (Pekala, 1989). Building on this method, T. Pérez-Poyatos et al. developed heteroatom-doped carbon gels using heterocyclic aldehydes as precursors, further expanding the versatility of AC materials (Pérez-Poyatos et al., 2025).

However, since ethylene is a nonpolar molecule, doping with heteroatoms can sometimes reduce adsorbate-adsorbent interactions, negatively impacting adsorption performance. Studies have shown that macropores, which are accessible to nitrogen at −196 °C, significantly influence the adsorption of ethylene, with structural properties playing a key role in determining overall adsorption capacity (Lim et al., 2020).

Recent advancements in AC-based ethylene scavengers have highlighted their potential for practical applications. For instance, Wang et al. developed activated carbon fibers (ACFs) from cellulosic biomass through reductive oxidation, achieving enhanced adsorption of nonpolar volatile organic compounds (VOCs), including ethylene, by reducing surface polarity (Wang et al., 2021). Similarly, Cao et al. demonstrated that acidified activated carbon powder (AACP) impregnated with $PdCl_2$ exhibited a maximum ethylene removal rate of 21.77 mL/g at 25 °C and 20.18 mL/g at 5 °C. This scavenger was also regenerable through heat treatment, showcasing its cost-effectiveness and reusability (Cao et al., 2015).

In Modified Atmosphere Packaging (MAP) systems for F&V preservation, granular activated carbon (GAC), particularly when doped with palladium (GAC-Pd), has been shown to effectively reduce ethylene accumulatio (G. Bailén, 2007; Gloria Bailen et al., 2006; Illeperuma & Jayasuriya, 2015). Ana M. Regadera-Macías et al. further optimized AC-based systems by synthesizing granular activated carbons with suitable microporosity and surface chemistry using CO_2 activation. Their findings suggest that agricultural waste-derived (such as olive stones) materials could provide sustainable and low-cost alternatives for ethylene scavenging (Regadera-Macías et al., 2024).

Innovative approaches to AC functionalization have also yielded promising results. For instance, Gundewadi et al. (Gundewadi et al., 2022) encapsulated 1–2 % of $PdCl_2$ in nanofibers, and the ethylene removal capacity (ESC) increased by 47–68 %. Lim et al. prepared carbon aerogels from pineapple leaf fibers, achieving an ethylene adsorption capacity of 1080 μmol/g at atmospheric pressure (Lim et al., 2020). Pannipa Tepamatr demonstrated the effectiveness of palladium-impregnated activated carbon (Pd/SAC), which minimized weight loss and reduced starch conversion in bananas during storage (Tepamatr, 2023). Fig. 2 illustrates the reduced weight loss in bananas

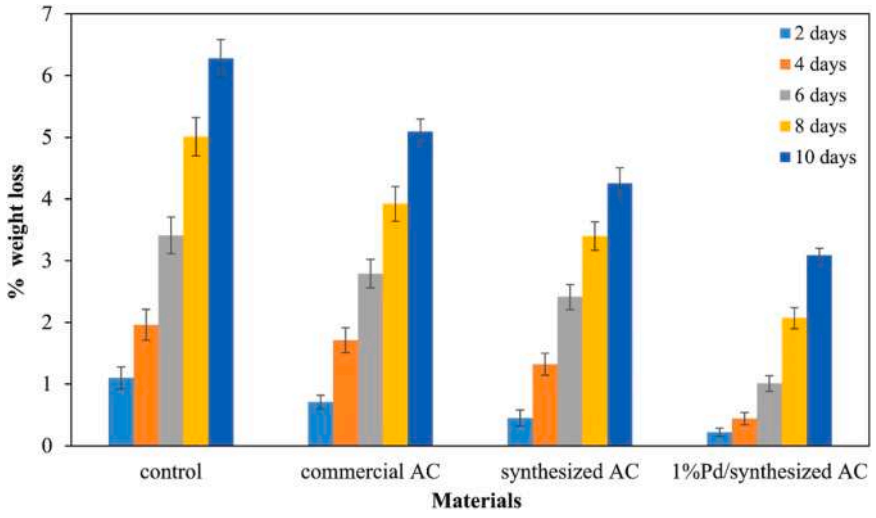


Fig. 2. Effect of activated carbon materials on weight loss of banana at 2, 4, 6, 8 and 10 days of storage.
(Adapted from Ref. (Tepamatr, 2023) Copyright 2023 Elsevier)

treated with 1 % Pd/SAC material over a 10-day storage period. All samples showed increasing weight loss over storage time, with 1 % Pd/SAC-treated bananas exhibiting the lowest weight loss percentage.

Another emerging approach involves the use of lignosulfonate-based carbon materials, which are rich in pore structures and derived from agricultural waste. Wang et al. showed that pyrolyzing lignosulfonates through a three-stage high-temperature process produced a variety of pore shapes and sizes, enhancing adsorption performance (S.-H. Wang et al., 2020). These lignosulfonate-based carbons not only offer competitive adsorption properties but also contribute to a circular economy by promoting the use of sustainable and cost-effective materials for ethylene removal.

Activated carbon and its derivatives, with their tunable physicochemical properties, continue to provide versatile and efficient solutions for ethylene removal in postharvest F&V preservation. The integration of functionalized AC materials with sustainable and low-cost production methods holds significant promise for advancing ethylene scavenging technologies.

2.1.2. *Metal-organic frameworks (MOFs)*

The efficiency of adsorption separations depends heavily on the properties of the adsorbent. Metal-organic frameworks (MOFs) represent a relatively new class of synthetic materials, which are composed of metal ions connected by organic ligands, forming a porous structure (Fig. 3) (Sosa et al., 2018), exhibiting superior adsorption capacity (Yongjia et al., 2025). The highly ordered crystalline structure of MOFs is composed of structured building blocks that can be assembled in various configurations, offering large, flexible pore sizes and tunable structures, along with several other desirable properties. In comparison to traditional porous materials such as activated carbon (Gao et al., 2016; Zhu et al., 2005) and zeolites (Pires et al., 2016; Hu et al., 2024), MOFs have garnered significant attention in gas adsorption applications due to their exceptional characteristics, including high porosity, large surface area, and tunable pore sizes (Li et al., 2020; Rieth et al., 2019).

Zhang et al. synthesized copper terephthalate (CuTPA) MOF using a solvothermal method and assessed its effectiveness for ethylene adsorption. In their study, the CuTPA MOF was placed in airtight containers with pre-ripened bananas and avocados, stored at 16 °C (Zhang

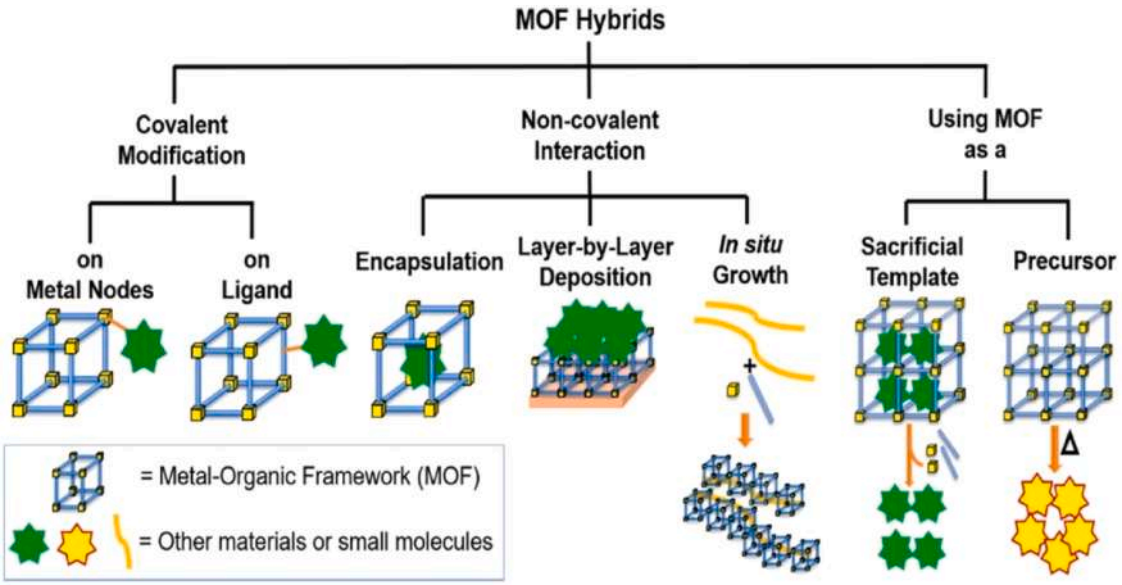


Fig. 3. MOF (metal-organic framework) hybrid preparation methods.
(Adapted from Ref. Copyright 2018 Multidisciplinary Digital Publishing Institute)

et al., 2016). Periodic monitoring of headspace gas composition, fruit color, and texture revealed that the CuTPA MOF had a high porosity, with a total pore volume of 0.39 cm^3/g. In a 4-liter container, 50 mg of CuTPA MOF could absorb up to 654 μL/L of ethylene. The study demonstrated that incorporating ethylene-loaded CuTPA MOF into post-harvest avocados and bananas promotes ripening by releasing ethylene, which stimulates pre-consumption processing.

Chopra et al. explored the potential of Basolite C300 and Basolite A520 MOFs for ethylene adsorption, noting that these materials were effective adsorbents in dry environments (Chopra et al., 2017). However, their adsorption efficiency decreased significantly in the presence of moisture. This study highlighted the potential of MOFs as systems for adsorbing, storing, and releasing gaseous compounds that influence plant physiology, indicating their promise as volatile plant growth regulators.

Research by Fan's team examined the use of high-intensity ultrasonication (HIU) to stretch the chemical structure of zein, improving the ethylene adsorption efficiency of D-zein films. This modification contributed to extending the shelf life of bananas (Fan et al., 2023). Similarly, Jiang et al. developed zein-based edible films containing nanoscale CA (catechin)/CD (cyclodextrinmetal)-MOFs. The incorporation of CA/CD-MOFs enhanced the films' water resistance, barrier properties, and mechanical strength. These films proved to be effective for direct food contact and extended the shelf life of food by improving the availability of active ingredients (Jiang et al., 2023).

Encapsulation of MOFs for different applications is a developing area of interest. While MOF powders have been utilized in pouches for ethylene adsorption and release in fresh produce packaging, consumer preference typically leans against free-floating pouches. Encapsulating MOFs into films presents a more attractive alternative, providing a larger surface area for ethylene adsorption without the need for separate pouches. Elangovan and Kazemi embedded MOFs into poly (lactic acid) (PLA) films, which demonstrated good physical, mechanical, optical, thermal, and thermo-mechanical properties (Elangovan et al., 2011; Kazemi et al., 2025). However, the ethylene adsorption potential of these MOF-containing films remains largely underexplored.

Further studies by Zhang et al. evaluated several commercial MOFs as ethylene adsorbents for controlling ripening and extending the shelf life of fresh produce during distribution (Zhang et al., 2023). Their study found that magnesium formate (MgF) MOF and aluminum hydroxide fumarate (AlF) MOF exhibited significantly higher ethylene adsorption capacities than the other six MOFs tested (C300, Cu, A520, Z377, ZIF-8, Z1200). MgF, in particular, proved to be the most effective ethylene adsorbent due to its stability across various temperatures, relative humidities, and ethylene concentrations. MgF-embedded low-density polyethylene (LDPE) films demonstrated a higher ethylene adsorption capacity than films embedded with PLA or polyvinyl alcohol (PVA). Furthermore, MgF-embedded LDPE films were effective in extending the shelf life of bananas under simulated shipping conditions, significantly slowing ripening and reducing waste, thus enhancing retail flexibility.

However, one of the disadvantages of using MOFs as ethylene scavengers is their relatively high cost compared to traditional adsorbents like activated carbon and zeolites. Despite this, the potential benefits of MOFs in improving the shelf life of fruits and vegetables could justify their use, particularly if advances in production methods reduce costs in the future.

2.1.3. Zeolites

Zeolites are widely recognized as effective carriers for ethylene absorbents due to their low cost, intricate porous structure, and high surface area. These characteristics make zeolites ideal for supporting catalysts, enhancing their performance in gas adsorption applications. As illustrated in Fig. 4, zeolites (*BEA-type) consist of 4–6 molecular rings (MRs) surrounding 12 MR channels, into which metal clusters, such as palladium (Pt), can be encapsulated for enhanced catalytic activity (Ma et al., 2021).

Leon A. Terry and Qiu P, demonstrated the potential of palladium (Pd)-impregnated zeolite powders for ethylene adsorption. Their study revealed that Pd-impregnated zeolite exhibited a significant ethylene adsorption capacity of 4162 μL/g at 20 °C and approximately 100 % relative humidity (RH), outperforming $KMnO_4$-based scavengers at low dosages and high RH. Importantly, the Pd material did not interfere with the subsequent ripening process, highlighting its commercial potential for ethylene removal in postharvest applications (Terry et al., 2007; Qiu et al., 2024).

Chlorine dioxide (ClO_2) is an efficient, broad-spectrum bactericidal, safe, and residue-free antibacterial agent (Ren et al., 2023). Aday and Caner explored the use of chlorine dioxide (ClO_2) and chabazite zeolite-filled activated pouches for maintaining the quality and extending the shelf life of strawberries (Aday & Caner, 2010). Their findings indicated that both low and high-dose active packaging treatments improved firmness, stickiness, and chewability compared to other treatments. These results suggest that active packaging systems incorporating ClO_2 and zeolite can significantly benefit strawberry preservation, though practical implementation would require careful consideration of packaging barrier properties, sachet concentration, and ClO_2 exposure time.

Esturk and colleagues examined the effectiveness of ethylene adsorbent zeolite (M2) incorporated into low-density polyethylene (LDPE) pouches for packaging broccoli florets (Esturk et al., 2014). The study revealed that control broccoli deteriorated rapidly, with significant mass loss, chlorophyll degradation, and stem hardening. In contrast, broccoli packaged in the M2 ethylene adsorbent film exhibited significantly reduced mass loss and delayed changes in quality. Soluble solids and phenol content remained stable over time, and after 20 days of storage, the ethylene concentration in the M1 film (without

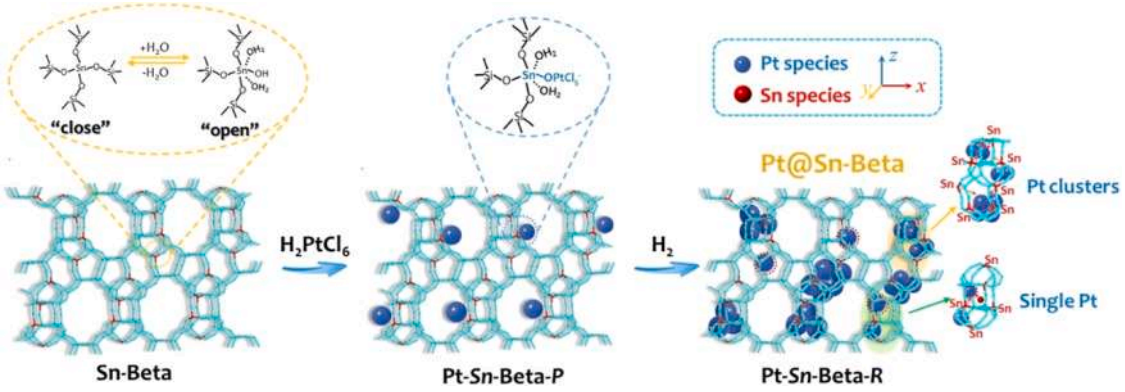


Fig. 4. Schematic representation of the proposed synthetic route for Pt single atoms and subnanometric clusters encapsulated in Sn-Beta (Pt_1&Pt_n@Sn-Beta). (Adapted from Ref. (Ma et al., 2021) Copyright 2021 Elsevier)

adsorbent) was 61.8 ppm, while in the M2 film (with adsorbent), it was reduced to 0.33 ppm. The M2-packaged broccoli maintained high-quality characteristics for up to 20 days, compared to only 5 days for the control, demonstrating the effectiveness of zeolite-based ethylene adsorption.

For packaging applications, films incorporating biopolymer-based adsorbents are emerging as an attractive alternative. Chitosan, a biodegradable biopolymer, has been used in food packaging due to its film-forming, antifungal, and antibacterial properties (Pires et al., 2018; Souza et al., 2018). When incorporated into chitosan films, zeolite can combine its adsorption capacity with the beneficial properties of chitosan. For instance, chitosan/zeolite (CZ) films, such as those containing 93 % zeolite (CZ93 L), exhibit similar or even superior ethylene adsorption compared to pure zeolite (ZR90) regenerated at 90 °C. Lyophilized CZ films demonstrated higher adsorption capacity than partially dried films. In contrast, dense chitosan films (DCF), porous chitosan films (PCF), and CZ films with lower zeolite content (e.g., 33 % zeolite) showed reduced ethylene adsorption efficiency. These findings highlight the strong potential of chitosan/zeolite films for food packaging applications.

Despite their promise, porous ethylene adsorbents face several drawbacks (Keller et al., 2013): (1) ethylene is adsorbed only on the surface or within the pores rather than being fully decomposed; (2) desorption of adsorbed ethylene may occur over time; (3) adsorption efficiency typically decreases as the adsorbent becomes saturated with ethylene; and (4) adsorbents require frequent replacement, which can be difficult and costly, particularly in large-scale applications (Kim et al., 2019).

Zeolite-based adsorbents offer a promising, cost-effective solution for ethylene removal in food packaging, with potential applications for enhancing the shelf life and quality of fresh produce. Future research will need to focus on overcoming the limitations associated with adsorbent saturation and desorption, as well as exploring the integration of zeolite adsorbents with other materials to improve performance and scalability.

2.2. Chemical elimination

The chemical elimination of ethylene primarily involves oxidation reactions to efficiently convert this compound into non-harmful products. This process can be divided into two main categories: direct oxidation using chemical reagents and catalytic oxidation technologies. The latter encompasses methods such as photocatalysis, thermal catalysis, and plasma catalysis. Each of these technologies employs different mechanisms to facilitate the oxidation of ethylene, offering distinct advantages depending on the reaction conditions and desired outcomes.

2.2.1. Direct catalytic oxidation

The use of potassium permanganate ($KMnO_4$) in combination with porous materials such as montmorillonite, seafoam, and zeolite has gained significant attention as a method for ethylene scavenging (Álvarez-Hernández et al., 2020; Álvarez-Hernández, Martínez-Hernández, Avalos-Belmontes, Rodríguez-Hernández et al., 2019). The rationale behind integrating $KMnO_4$ with these porous materials is to increase the exposure of $KMnO_4$ to air, thus enhancing its surface area and oxidizing effectiveness (Warton, 2004; Su et al., 2024). Furthermore, a synergistic effect is generated through the creation of an adsorption-oxidation system. This system combines the physical adsorption properties of the porous material with the chemical oxidation capabilities of $KMnO_4$ (Ayman Mohammed El-Anany, 2013; Gaikwad et al., 2019), facilitating ethylene adsorption onto the surface of the material, where it is subsequently oxidized by $KMnO_4$. $KMnO_4$ is considered one of the most efficient reagents for converting ethylene into water and carbon dioxide under various conditions (Álvarez-Hernández, Martínez-Hernández, Avalos-Belmontes, Castillo-Campohermoso et al., 2019). The oxidation reaction is represented by the following equation:

$$3C_2H_4 + 12KMnO_4 \rightarrow 12MnO_2 + 12KOH + 6CO_2$$ (Keller et al., 2013)

Wang and Ajji developed an innovative ethylene scavenger by combining pumice and $KMnO_4$. Their study demonstrated that smaller particle sizes and lower relative humidity enhanced ethylene adsorption capacity. The optimal pumice-to-$KMnO_4$ ratio was found to be 1 g:100 mg, which resulted in an ethylene adsorption capacity of approximately 620 μL/g within 24 h at a relative humidity of 30 %. This formulation was able to extend the shelf life of avocados by one week (Wang & Ajji, 2022a). In a related study, they synthesized an ethylene-scavenging film from low-density polyethylene (LDPE) incorporating a mixture of pumice and $KMnO_4$ (10:1 by weight) as the active agent, with maleic anhydride-grafted polyethylene (PE-g-MA) as a bulking agent. This film, containing 3wt % active agent, was synthesized at 25 °C. It successfully preserved avocados for 20 days by inhibiting ethylene and carbon dioxide concentrations in the packaging headspace, significantly reducing the loss of fruit firmness. In contrast, avocados packaged in pure LDPE film only lasted 10 days. While pure LDPE films cannot remove ethylene, the addition of an activator enables effective scavenging. The ethylene removal capacity of LDPE-based films is influenced by the content and distribution of the activator (Ebrahimi et al., 2021). Fig. 5 shows that films with 1–3 wt % activator maintained good dispersion without significant aggregation. Under these conditions of comparable dispersibility, ethylene removal capacity depended primarily on active agent content, with the LDPE-3 %$KMnO_4$ film demonstrating optimal performance (Wang & Ajji, 2022b). This superior performance is attributed to the homogeneous dispersion of the low-loading activator, whereas high activator concentrations caused particle aggregation, making the 3 wt % formulation the most effective for ethylene removal.

Álvarez-Hernández et al. took a similar approach by loading $KMnO_4$ onto seafoam, which showed improved performance compared to a commercially available scavenger ($KMnO_4$-loaded zeolite). The $KMnO_4$-loaded seafoam scavenger proved particularly effective in maintaining favorable packing gas compositions at 2 °C or 15 °C, delaying the ripening process and prolonging the quality of fresh apricots. Notably, this new scavenger required 50 % less material than the commercial alternative, offering a more cost-effective post-harvest solution (Álvarez-Hernández et al., 2020).

Arezoo Ebrahimi and colleagues developed nanocomposites based on polyolefin elastomers (POEs) to improve barrier and mechanical properties for ethylene scavenging. By impregnating nanoparticles such as nanosilica (NS) and nanoclay (NC) with $KMnO_4$, they produced films with enhanced mechanical properties, greater elongation at break (EA), and lower water vapor permeability (WVP) compared to pure POE films. These nanocomposite films exhibited increased ethylene uptake with higher concentrations of impregnated nanoparticles. The optimized films extended the shelf life of bananas up to 15 days under ambient conditions (Ebrahimi et al., 2021). Bananas packaged in these films remained green and unripe on day 7, whereas control samples turned yellow.

Jaewon Joung et al. incorporated $KMnO_4$-impregnated halloysite nanotubes (P-HNTs) into an LDPE matrix as an encapsulation material for ethylene scavengers. Their findings showed that although incorporating P-HNTs into LDPE did not optimize the mechanical and barrier properties of the films, a 1 g/100 g loading of P-HNTs significantly enhanced the thermal stability, crystallinity, and ethylene scavenging capacity of the nanocomposites (by 1700 %). Cherry tomatoes wrapped in a 1 % P-HNTs/LDPE nanocomposite film and stored at 20 °C for 21 days exhibited lower ethylene production rates, reduced respiration rates, and delayed firmness loss and color changes compared to control samples (Joung et al., 2021).

Du et al. (Du et al., 2024) immobilized $KMnO_4$ particles in silicone rubber (107 SR), preventing direct contact with bananas while ensuring firm anchoring on the carbon black (CB) surface. The uniformly porous

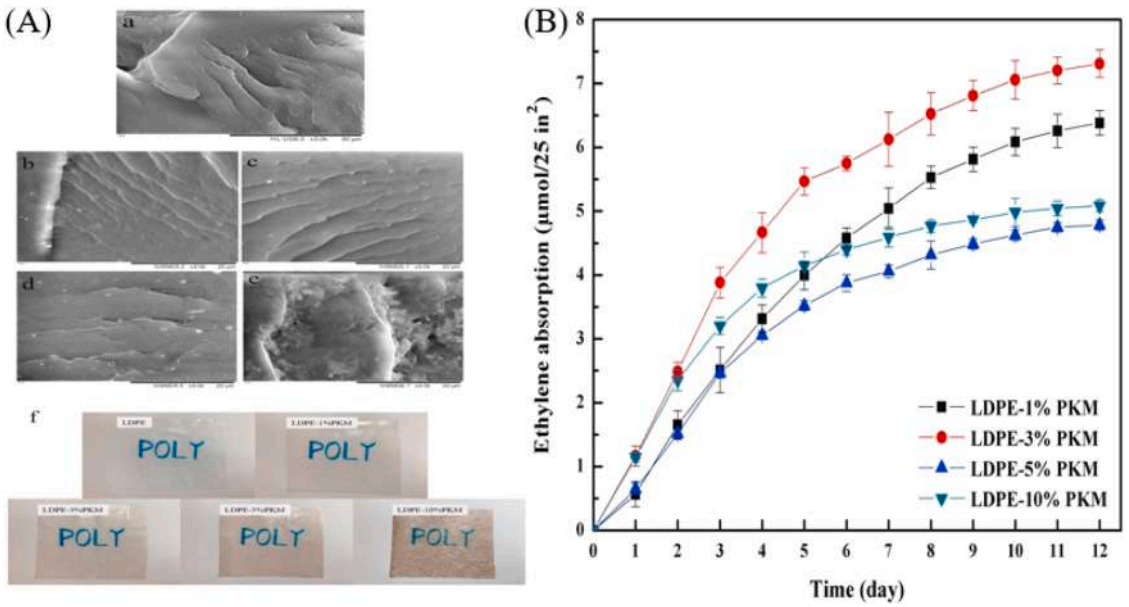


Fig. 5. (A)Ethylene scavenging capacity of LDPE-based films. (B) SEM cross-sectional images of LDPE-based films: (a) LDPE, (b) LDPE-1 %PKM, (c) LDPE-3 %PKM, (d) LDPE-5 %PKM, and (e) LDPE-10 %PKM; (f) photographs of films.
(Adapted from Ref. (Wang & Ajji, 2022b) Copyright 2022 Elsevier)

structure of 107 SR facilitates ethylene diffusion, enabling oxidation by $KMnO_4$ into CO_2. This dual-layer coating combines ethylene removal (preservation layer) and moisture retention (superhydrophobic layer), synergistically extending banana shelf life.

2.2.2. *Photocatalytic oxidation*

Photocatalytic oxidation (PCO) has emerged as a promising approach for ethylene removal, leveraging light-activated catalysts to oxidize ethylene into carbon dioxide (CO_2) and water (H_2O). This process primarily employs semiconductors with suitable bandgaps, such as titanium dioxide (TiO_2), palladium, and platinum, which facilitate chemical oxidation reactions (Hua et al., 2024; Xu et al., 2023). PCO has demonstrated significant potential not only for ethylene removal but also for environmental sterilization, enhancing its attractiveness as a green and efficient technology (H. Yang, Ma, Zhang et al., 2018).

The underlying mechanism of PCO involves the absorption of photon energy by the photocatalyst, leading to the excitation of electrons and the formation of electron-hole pairs. These pairs interact with oxygen and water molecules to generate reactive oxygen species (ROS), which oxidize ethylene into CO_2 and H_2O (Pathak et al., 2019). Titanium dioxide (TiO_2), one of the most widely studied photocatalysts, is particularly notable due to its chemical inertness, high photostability, low cost,

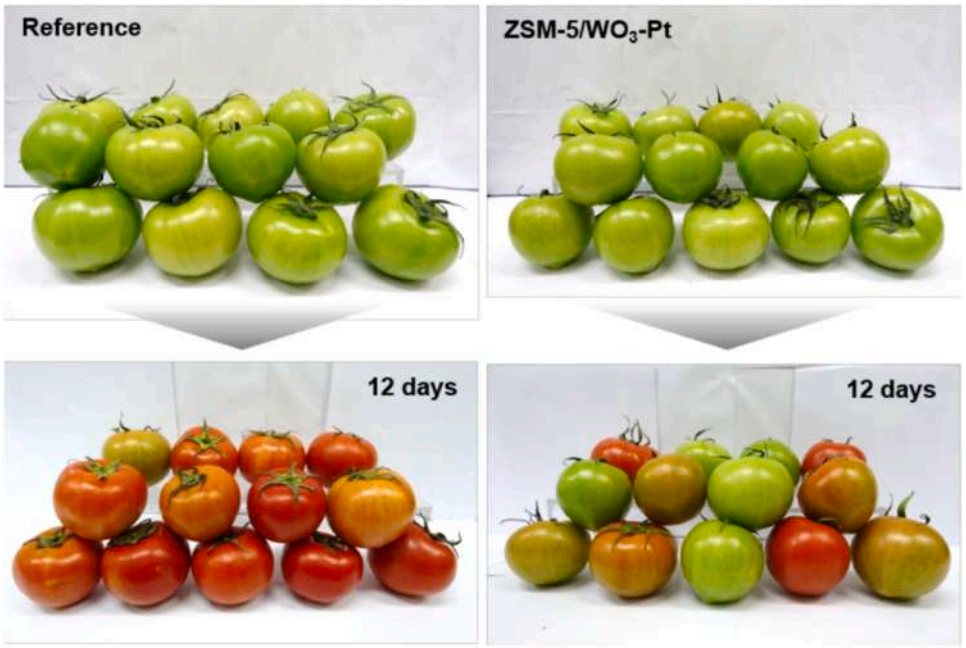


Fig. 6. Changes of tomato color after storage with (right) and without (left) the photocatalytic module. Storage conditions: temperature 20−25 °C, humidity 45−55 %.
(Adapted from Ref.(Kim et al., 2019) Copyright 2019 American Chemical Society)

and environmental safety. Park et al. (Dal-Rung Park et al., 1999) demonstrated the complete oxidation of ethylene on powdered TiO_2 surfaces under UV light, highlighting the role of hydroxyl radicals and superoxide ions in the degradation process.

Recent advancements in PCO have focused on optimizing photocatalyst performance. For instance, Kim et al. developed a visible-light-activated Pt-loaded monoclinic WO_3 nanorod composite (ZSM-5/WO_3-Pt) supported on ZSM-5 (Kim et al., 2019). The composite's microporous structure allowed hydroxyl radicals generated by WO_3-Pt to migrate into ZSM-5 pores, facilitating ethylene adsorption and decomposition during fruit storage. This innovation eliminated the need for additional recycling devices and proved effective in reducing surface spoilage, as evidenced by color retention in stored tomatoes (Fig. 6).

Similarly, TiO_2-Bi_2WO_6 composites have gained attention for their visible-light-driven ethylene degradation capabilities (Fig. 7(a)) (R. Wang et al., 2020). The spherical TiO_2-Bi_2WO_6 structure enhances photocatalytic activity through its porous surface, which increases adsorption sites and inhibits electron-hole recombination. Experimental data suggest that a 10 wt % TiO_2 loading on Bi_2WO_6 achieves the highest ethylene degradation rate, while excessive TiO_2 loading offers no significant improvements (Fig. 7(c)). The ethylene degradation rate initially increases and then decreases with higher TiO_2 loading, indicating that an optimal amount of nano-TiO_2 enhances visible-light photocatalytic performance. This improvement arises from complementary band structures between the two materials, which form a type-II (TB) heterojunction. The heterojunction broadens the spectral response range of TiO_2 into the visible region while creating an interfacial potential gradient that promotes charge separation. Consequently, the recombination of photogenerated electrons and holes on Bi_2WO_6 is suppressed, improving quantum efficiency and overall photocatalytic activity. These findings underscore the importance of material optimization in achieving efficient ethylene removal.

The application of PCO extends beyond catalyst design to practical storage solutions (Michael A. Gonzalez, 1999). Maneerat and Fonseca reported that TiO_2 photocatalysis effectively degraded ethylene under high-humidity conditions, delaying tomato and papayas ripening. Their study emphasized the role of TiO_2 concentration and UV-A light intensity, showing that a combination of 10 g TiO_2 and 5 W/m^2 UV-A light removed over 90 % of ethylene (Fonseca et al., 2021; Maneerat et al., 2003). Notably, TiO_2 also reduced volatile compounds like acetaldehyde and ethanol, which contribute to off-flavors. However, its effectiveness in managing these byproducts diminished over extended storage periods, indicating the need for further optimization.

Alternative methods, such as vacuum ultraviolet photolysis (VUV), have also shown promise. Pathak et al. demonstrated that VUV irradiation (185 nm) effectively oxidized ethylene in a mixed-fruit storage chamber, reducing ethylene concentrations from 5 μL L^{-1} to 1.8 μL L^{-1} within a laboratory-scale reactor (Pathak et al., 2017). While effective, the limited penetration depth of UV light in porous catalysts remains a challenge, necessitating advanced catalyst designs that address this

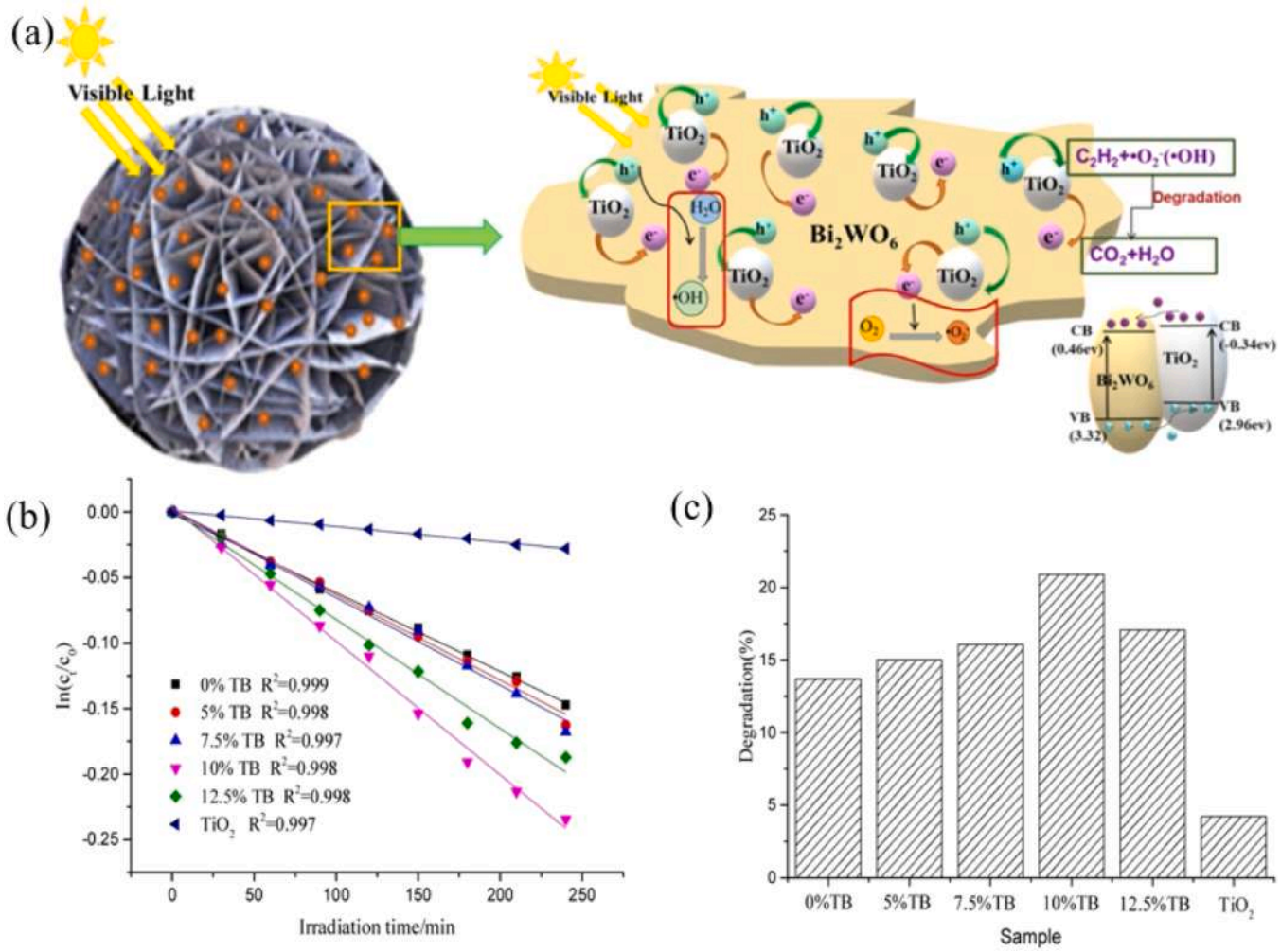


Fig. 7. a: A schematic representation of the photocatalytic enhancement mechanism by TB; b: Kinetics of ethylene degradation for the different photocatalysts; c: Ethylene degradation of different photocatalysts.
(Adapted from Ref. (R. Wang et al., 2020) Copyright 2020 Elsevier)

limitation.

Despite its promise, PCO faces several challenges that hinder widespread adoption. Catalyst deactivation over time, photon energy loss, and electron-hole recombination reduce efficiency (Namrata Pathak et al., 2017; Tytgat et al., 2012; vorgelegt von M.Tech, 2019). Additionally, prolonged UV exposure may negatively impact stored food quality, requiring careful management (Yildirim et al., 2017). Addressing these issues through catalyst modification and system optimization will be crucial for advancing PCO technologies in postharvest ethylene removal.

Photocatalytic oxidation represents a green and efficient method for ethylene scavenging, with significant potential in extending the freshness of perishable produce (Michael A. Gonzalez, 1999; Lu et al., 2025). However, its practical implementation requires overcoming efficiency and durability challenges to fully realize its benefits in postharvest management systems.

2.2.3. *Plasma-catalyzed oxidation*

Plasma treatment technologies offer an efficient method for decomposing ethylene at atmospheric pressure and low temperatures. By leveraging a variety of reactive oxygen species (ROS), these systems can rapidly degrade ethylene across a range of concentrations (Takahashi et al., 2018; Ye et al., 2013). However, their standalone application is often hindered by low selectivity for carbon dioxide (CO_2) as the final product and the generation of undesirable byproducts, including aldehydes and organic acids. To overcome these limitations, hybrid plasma-catalysis systems have been developed to enhance selectivity, energy efficiency, and process effectiveness (Feng et al., 2018; Trinh & Mok, 2015).

Among plasma-based methods, dielectric barrier discharge (DBD) plasma stands out due to its compatibility with catalytic systems. Mok et al. demonstrated the effectiveness of a hybrid plasma-catalytic oxidation reactor that combined DBD with a Pd/ZSM-5 catalyst (Mok et al., 2020). The system operated on adsorption-enrichment cycles followed by plasma-catalyzed oxidation decomposition of ethylene. When tested for long-term storage of Fuji apples, this method significantly reduced ethylene levels, maintaining higher fruit firmness, sugar content, and acidity. Notably, the treated apples exhibited a decay rate of only 1 % compared to 10 % in untreated controls, underscoring the potential of plasma-catalyzed oxidation systems to extend the shelf life of fresh produce.

To further optimize the process, Mok and colleagues designed a compact DBD plasma reactor incorporating catalytic adsorbents. The system demonstrated complete oxidation of adsorbed ethylene to CO_2 at significantly lower decomposition temperatures (~160 °C) compared to catalyst-only systems (~280 °C), with optimal palladium concentrations

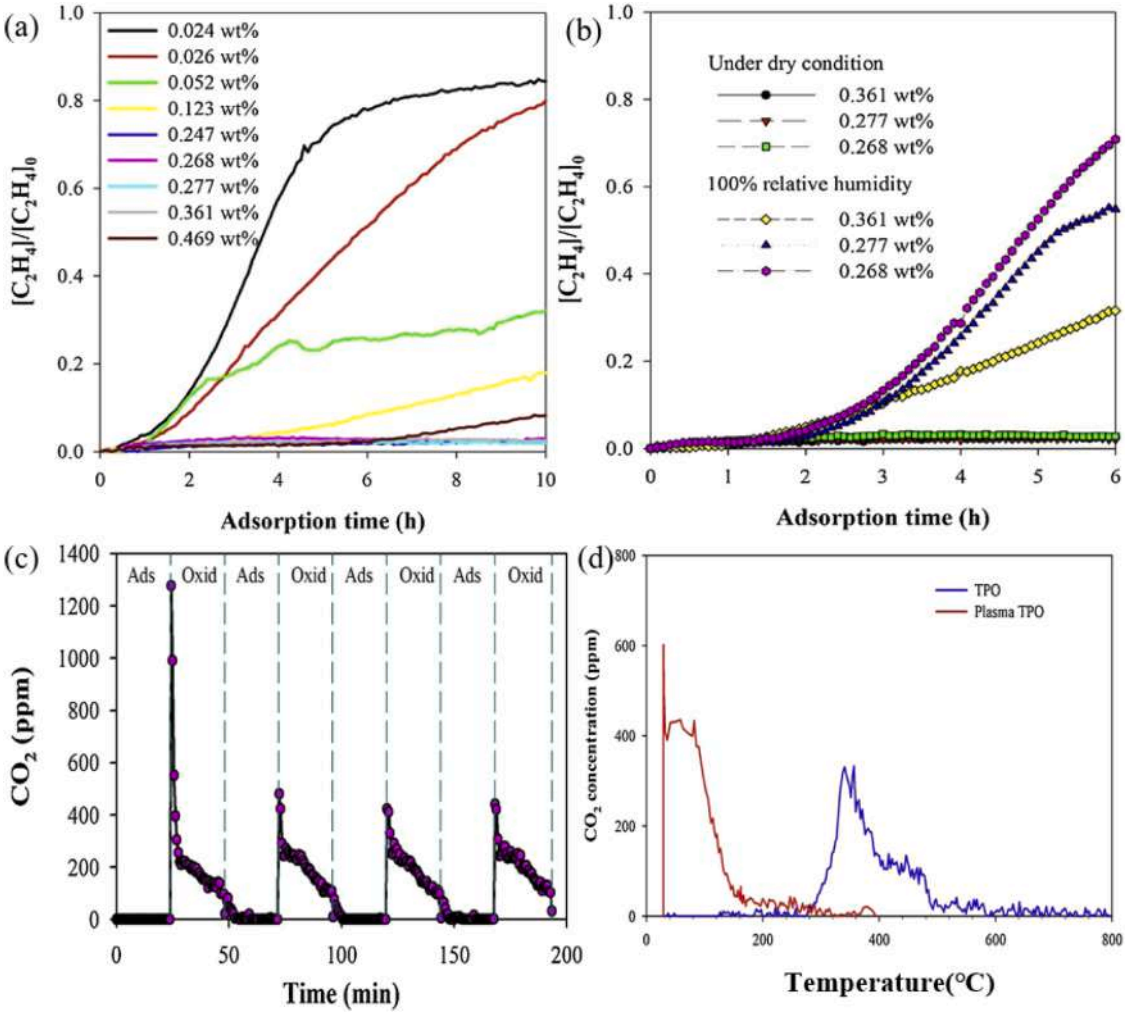


Fig. 8. (a)Dependence of ethylene adsorption on palladium loading (ZSM-5: 20 g; feed gas flow rate: 2 L min^{-1}; inlet C_2H_4: 20 ppm; dry conditions).(b) Effect of humidity on the adsorption of ethylene (Pd/ZSM-5: 20 g; feed gas flow rate: 2 L min^{-1}; inlet C_2H_4: 20 ppm; dry conditions).(c) Cyclic operation of the plasma-catalytic reactor: variation in the CO_2 concentration with time (Pd/ZSM-5: 10 g; feed gas flow rate: 2 L min^{-1}; inlet C_2H_4: 200 ppm; dry conditions).(d)Temperature programmed oxidation of ethylene with and without plasma (Pd/ZSM-5: 10 g; feed gas flow rate: 2 L min^{-1}).
(Adapted from Ref. (Mok et al., 2019) Copyright 2019 Elsevier)

ranging from 0.268 % to 0.361 % (Fig. 8) (Mok et al., 2019). Storage tests with kiwifruit and cauliflower confirmed improved stability and reduced spoilage, reinforcing the applicability of plasma-catalyzed oxidation for postharvest storage solutions.

Filled-bed DBD plasma reactors have also been investigated for their energy efficiency and scalability. Saud et al. developed a cellular plasma reactor integrating a Pd/ZSM-5/monomer (Pd-ZCM) catalyst within perforated electrodes (Fig. 9) (Saud et al., 2022). By optimizing the catalyst's binder content (8 %) (Fig. 10), the system achieved superior ethylene conversion efficiency while maintaining low energy consumption (~36 J/L for cyclic plasma-catalytic operation). This setup demonstrated stable performance under high-humidity conditions, with no detectable toxic byproducts, making it a promising approach for agricultural storage.

Despite these advancements, challenges such as the high energy demands for plasma generation and the risk of byproduct formation limit the large-scale implementation of plasma-catalyzed oxidation. Continued efforts to enhance energy efficiency, minimize byproduct

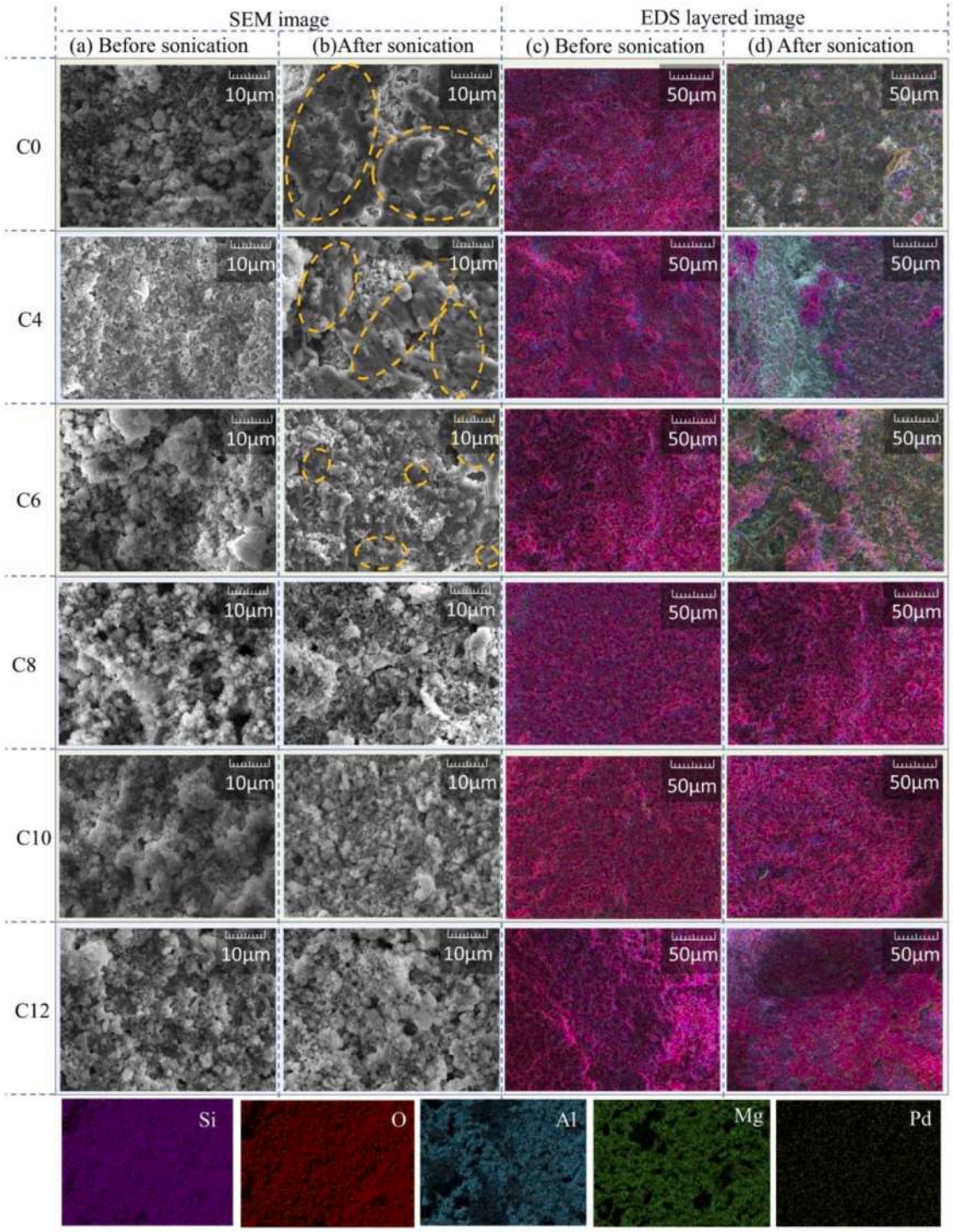


Fig. 9. Surface morphology and EDS mapping of the surface of the catalyst coating (a) before, (b) after and (c) before, (d) after ultrasonic cleaning (sonication time: 120 min).
(Adapted from Ref. (Saud et al., 2022) Copyright 2021 Elsevier)

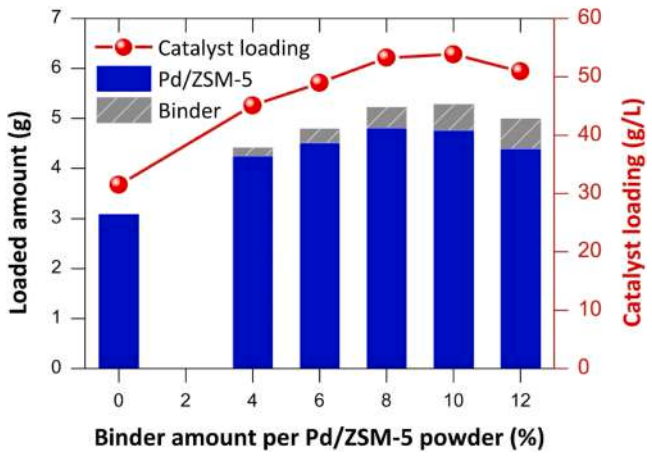


Fig. 10. Effect of binder content on the amount of Pd/ZSM-5 powder loaded onto the monolith.
(Adapted from Ref. (Saud et al., 2022) Copyright 2021 Elsevier)

formation, and refine hybrid system designs are critical for broader adoption.

In comparison, conventional ethylene removal methods such as physisorption and chemisorption remain in use, each with distinct advantages and limitations (Table 3). Table 4 summarizes the comparative analysis of ethylene adsorbents, including cost, safety, reaction kinetics, and environmental impact. While physisorption offers reversible ethylene capture with low energy requirements, it lacks selectivity and efficiency under variable conditions. Chemisorption, though more selective, requires higher energy inputs and is prone to catalyst deactivation.

Plasma-catalyzed oxidation, particularly through DBD systems integrated with catalysts like Pd/ZSM-5, represents a promising technology for ethylene removal. Its ability to combine energy efficiency with effective ethylene degradation positions it as a viable alternative to traditional methods for enhancing the shelf life of ethylene-sensitive agricultural products. Future innovations in energy optimization and system scalability will be essential to addressing current limitations and enabling widespread adoption.

3. Metal-based catalysts for ethylene elimination

Although physical adsorption initially offers operational simplicity for ethylene capture, its limitations—including reduced efficiency at low ethylene concentrations, high energy demands for high-temperature regeneration, and the inability to degrade pollutants (only transferring their phase)—render it inadequate for long-term, high-efficiency

Table 3
Advantages and disadvantages of physical adsorption and chemical adsorption.

Adsorption classification	Methods	Absorbent	Advantages	Disadvantages	Ref.
Physical adsorption	Adsorption	Activated carbon(van der Waals forces), MOF(π -complexation), Zeolites(π -complexation)	Porous structure, good chemical stability, non-toxic, easy to recycle	Ethylene is adsorbed only in the pores or acidic sites and cannot be eliminated, adsorption efficiency decreases with time; desorption is possible, adsorbent needs to be changed frequently	(Wei et al., 2021) (Terry et al., 2007) (Smith et al., 2009) (Cisneros et al., 2019) (Zeng et al., 2019) (Anwer et al., 2021)
Chemical adsorption	Direct catalytic oxidation	$KMnO_4$(Mn-O covalent bonds)	High ethylene removal efficiency and relatively inexpensive	Forms by-products; tends to absorb water leading to loss of efficiency, requires frequent replacement, numerous health, environmental and safety hazards	(Tirgar et al., 2018) (Sardabi et al., 2014) (Minas et al., 2012) (Minas et al., 2014) (Du et al., 2023)
	Photocatalytic oxidation	TiO_2(oxygen vacancies)	Green and clean technology with relatively low energy demand	Limited oxidizing capacity, requires additional light source to generate excited holes and electrons	(Kim et al., 2019) (Tytgat et al., 2012) (Namrata Pathak et al., 2017) (Kaewklin et al., 2018)
	Plasma-catalyzed oxidation	Pd/zeolites (π -complexation oxidation)	Higher ethylene removal efficiency	Excessive energy demand for CO_2 and poor CO_2 selectivity with risk of by-product emissions	(Mok et al., 2020) (Mok et al., 2019) (Saud et al., 2022) (Trinh et al., 2015) (Chen et al., 2023) (Zhou et al., 2022)

Table 4
A summary of the cost, safety, kinetics and environmental impact of ethylene adsorbents.

Adsorbent Materials	Cost	Safety (Considerations for Food Contact)	Kinetics (Adsorption Rate)	Impact of Environmental Factors	Ref.
Potassium permanganate ($KMnO_4$) loaded materials (e.g., loaded on zeolite, silica gel, etc.)	Low	Highly toxic, with deep purple color that is easy to migrate, generally not used in packaging in direct contact with food	Relatively slow, requiring a certain time to oxidize ethylene	Little affected by humidity, but high temperature may accelerate its failure	(Warton, 2004)
1-Methylcyclopropene (1-MCP)	Medium	No residual toxicity, but may cause diseases in fruits	Fast, can quickly bind to ethylene receptors	Affected by temperature, stable effect at low temperatures	(Wang et al., 2025)
Metal oxide catalysts (e.g., TiO_2, Co_3O_4, etc.)	High	Some need to assess the risk of heavy metal migration, and some are certified for use in specific food contact scenarios	Fast under photocatalysis or low-temperature catalysis	Light and temperature affect catalytic activity, and humidity may affect the stability of some catalysts	(Xue et al., 2011)
Nanoscale molecular sieves (zeolites, MOFs, etc.)	Medium-high	Non-toxic, some need to optimize hydrophobicity to avoid inactivation due to moisture	Relatively fast, large specific surface area is conducive to rapid adsorption	Greatly affected by humidity, the performance of some molecular sieves decreases under high humidity	(Yejee Ha et al., 2024; Chopra et al., 2017)
Activated carbon / porous carbon	Low	Non-toxic, high energy consumption for regeneration after adsorption saturation	Relatively fast, with obvious initial adsorption rate	Less affected by humidity, may desorb at high temperatures	(Oliveira et al., 2024)

purification. Consequently, advanced methods enabling direct ethylene conversion into CO_2 and H_2O at ambient or low temperatures have emerged as a critical breakthrough (Chen Lizhu et al., 2021). Among these, metal-based catalysts are particularly promising due to their tunable active sites and structural modularity, driving a shift toward high-efficiency, low-carbon ethylene elimination technologies (Zhang et al., 2022).

Metal-based catalysts exhibit synergistic physisorption-chemical processes that enhance ethylene removal efficiency. Mansourbahmani et al. (Mansourbahmani et al., 2017) systematically compared ethylene scavengers in tomato storage (7 ± 0.5 °C, 90±2 % RH, 35 days), demonstrating the following efficacy order: Pd-loaded nanozeolite (5 %) > $KMnO_4$-loaded nanozeolite (20 %) > 1-MCP (30 ppm) > SA (1 %) ≈ $CaCl_2$ (2 %) > UV-C (15 min). Complementary work by Jiang et al. (Jiang et al., 2013) revealed Pt/MCM-41 achieved near-complete ethylene degradation, outperforming Pt on SiO_2, Al_2O_3, ZrO_2, or TiO_2 supports. These studies collectively establish that porous-supported noble metal catalysts (Pd, Pt) offer superior ethylene removal compared to chemical or physical treatments.

3.1. *Precious metal catalysts*

The direct oxidation approach, relying on strong oxidants like $KMnO_4$ or ozone (O_3), has become less popular due to concerns over environmental impact, safety, and residue accumulation (Minas et al., 2012, I.S. 2018, 2014; Toti et al., 2017). Photocatalysis and plasma catalysis (Jiang et al., 2013; Kaewklin et al., 2018; Ma et al., 2009; Namrata Pathak et al., 2017; Tytgat et al., 2012; H. Yang, Ma, Zhang et al., 2018), though promising, face limitations such as low quantum efficiency of titanium dioxide (TiO_2) and the need for additional devices, which reduce practical applicability. In contrast, noble metal catalysts provide a more efficient alternative for ethylene oxidation at ambient temperatures, without requiring extra energy input, aligning with energy-saving and carbon-reduction goals.

The interaction between precious metals and their supports is crucial for ethylene oxidation efficiency. When the interaction between metal and carrier is weak, the carrier merely disperses the metal, and oxidation occurs solely on the metal surface. Stronger interactions enable surface defects on the carrier to activate oxygen, which then reacts with ethylene adsorbed on the metal surface (Xue et al., 2011). Zeolites, particularly acidic ones like ZSM-5, offer advantages over traditional oxide supports due to their unique steric structure, aiding olefin oxidation. For instance, Yang et al. demonstrated that using ZSM-5 zeolite as a support for silver (Ag) allowed for a 42 % ethylene conversion at room temperature, with the SiO_2/Al_2O_3 ratio playing a key role (H. Yang, Ma, Li et al., 2018). The catalytic stability of ethylene oxidation is primarily influenced by the number of Brønsted acid sites, which depends on the SiO_2/Al_2O_3 ratio due to its effect on both the quantity and strength of acid sites. The reaction mechanism proposed for ethylene oxidation on Ag/Zeolite showed how the oxidation process differs under dry versus humid conditions. In dry conditions, water adsorbs on Brønsted acid sites, creating OH groups that deactivate the catalyst (Fig. 11) (H. Yang, Ma, Zhang et al., 2018). However, in humid conditions, free OH groups and hydrogen-bonded OH groups keep some Brønsted acid sites active. This finding was confirmed through pyridine FTIR and MAS NMR spectroscopy, revealing that Brønsted acid sites are critical for catalyzing ethylene oxidation.

Recent progress in ethylene removal has shown considerable advancements in Pt-based and Ag-based catalysts operating at ambient temperatures. Pt/MCM-41, Pt/SBA-15, and Ag/zeolite catalysts have demonstrated excellent performance in ethylene oxidation at low temperatures. Jiang et al. showed that Pt catalysts supported on silica could fully oxidize ethylene, with 1 % Pt-loaded silica achieving over 99.8 % ethylene conversion at 0 °C (Jiang et al., 2013). However, water formed during oxidation caused gradual deactivation of the catalysts. To mitigate this, Satter et al. enhanced the hydrophobicity of mesoporous silica (SBA-15) through calcination, which improved ethylene conversion and CO_2 yield by preventing water buildup and preserving the activity of Pt sites (Satter, Hirayama et al., 2018, S.S. 2018).

Palladium-loaded activated charcoal also showed promise, with Gloria et al. reporting that 1 % Pd-loaded activated charcoal outperformed untreated charcoal in preserving tomato quality (Gloria Bailen et al., 2006). Palladium-impregnated zeolites have similarly proven effective in removing ethylene and extending the shelf life of fruits like bananas and avocados (Namrata Pathak et al., 2017; Smith et al., 2009; Terry et al., 2007). Additionally, gold (Au)-based catalysts, particularly Au/Co_3O_4, have attracted attention for their ability to catalyze ethylene oxidation at room temperature. Li and Hao (Jinjun Li et al., 2008; Hao et al., 2022) found that 4 % Au/Co_3O_4 outperformed other materials like Fe_2O_3, TiO_2, and ZnO in ethylene elimination, although it deactivated quickly at high ethylene concentrations. Ma et al. demonstrated that gold nanoparticles on Co_3O_4 achieved near-complete oxidation of 50 ppm ethylene at 0 °C (Jinjun Li et al., 2008; Ma et al., 2009; Xue et al., 2011). Similarly, Xue et al. synthesized Co_3O_4 materials with various morphologies (Fig. 12), showing that Au/Co_3O_4 nanorod catalysts had the highest ethylene conversion efficiency (93.7 %) due to oxygen vacancies that facilitated the oxidation process (Xue et al., 2011).

Silver-based catalysts, such as Ag/ZSM-5, are also commonly studied for ethylene removal, primarily through adsorption. However, ethylene adsorption on silver surfaces is challenging due to silver's electronic properties, although stable π-complexes can form between silver ions

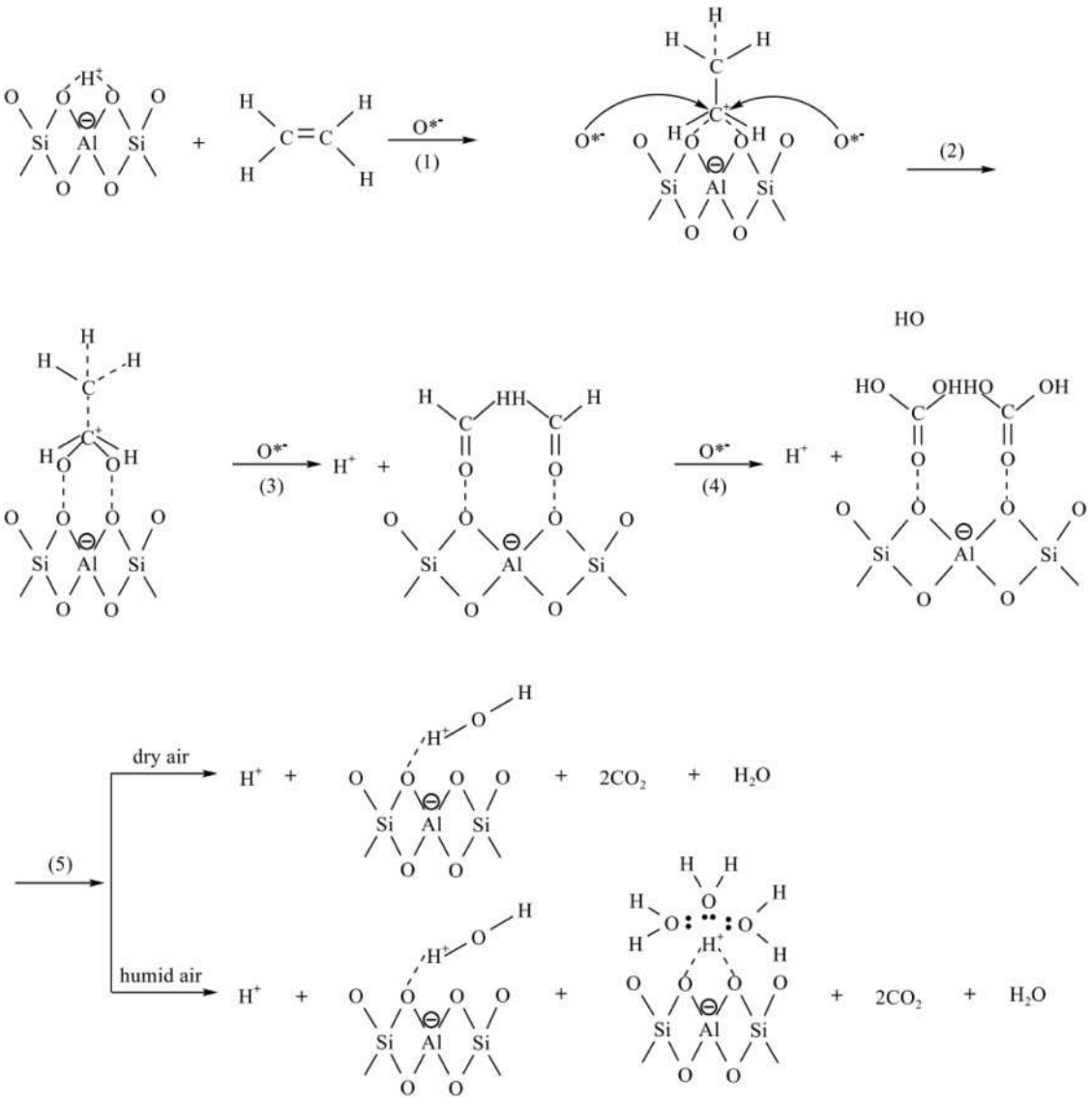


Fig. 11. Proposed mechanism of ethylene oxidation over Brønsted acid sites in Ag/zeolite catalysts, including five distinct steps that are illustrated below. (i) Ethylene binding to the Brønsted acid sites. (ii)Active oxygen species attacking the adsorbed ethylene species. (iii)Breaking of the carbon−carbon bond of the adsorbed ethylene species, forming formaldehyde species. (iv) Formation of carbonic acid species. (v) Under a dry atmosphere, the generation of CO_2 and H_2O; H_2O molecules bound to the Si−*O*−Al sites to consume Brønsted acid sites. For Ag/ZSM-5 and Ag/Beta under a humid atmosphere, more H_2O molecules around Brønsted acid sites formed hydrogen bonds with Brønsted acid sites.
(Adapted from Ref. (H. Yang, Ma, Zhang et al., 2018) Copyright 2018 Elsevier)

and ethylene. Studies by Yang et al. showed that Ag/ZSM-5 with a SiO_2/Al_2O_3 ratio of 38 exhibited strong catalytic stability (Fig. 13) (H. Yang, Ma, Li et al., 2018), maintaining nearly 100 % ethylene conversion for 405 min before gradually declining. This drop in efficiency was linked to the competitive adsorption of ethylene and water vapor, which hindered ethylene adsorption at the Brønsted acid sites.

While Pt-based, Au/Co_3O_4, and Ag/ZSM-5 catalysts show significant potential for ethylene removal, challenges such as catalyst deactivation and stability, particularly in the presence of water vapor, need further optimization for large-scale applications.

3.2. Transition metal catalysts

Ethylene scavengers are essential in controlling ethylene production and degradation to extend the shelf life of fruits and vegetables. Commercially available ethylene scavengers include potassium permanganate ($KMnO_4$), zeolites, and activated carbon. Titanium dioxide (TiO_2), though not widely commercialized, holds great promise as an ethylene scavenger due to its ability to degrade ethylene into carbon dioxide (CO_2) and water (H_2O) under ultraviolet (UV) light. TiO_2 offers advantages over traditional adsorption methods by fully degrading ethylene (Hussain et al., 2010; Yi et al., 2025), as well as being reusable, chemically stable, eco-friendly, and non-toxic. This makes TiO_2 ideal for applications in food storage and preservation (Enescu et al., 2020; Suharyadi et al., 2023; Syauqi et al., 2023).

Several studies have explored TiO_2 in various forms such as films, coatings, and powders for fruit storage. Siripatrawan and Kaewklin investigated chitosan-TiO_2 nanocomposites as active packaging materials for ethylene scavenging and antimicrobial activity (Siripatrawan & Kaewklin, 2018). The TiO_2 content significantly enhanced ethylene photodegradation (Fig. 14). Similarly, Kaewklin et al. created chitosan films with TiO_2 nanoparticles to delay the ripening of cherry tomatoes, showing improved storage quality under UV light (Kaewklin et al., 2018). Additionally, titanium dioxide-coated polypropylene films

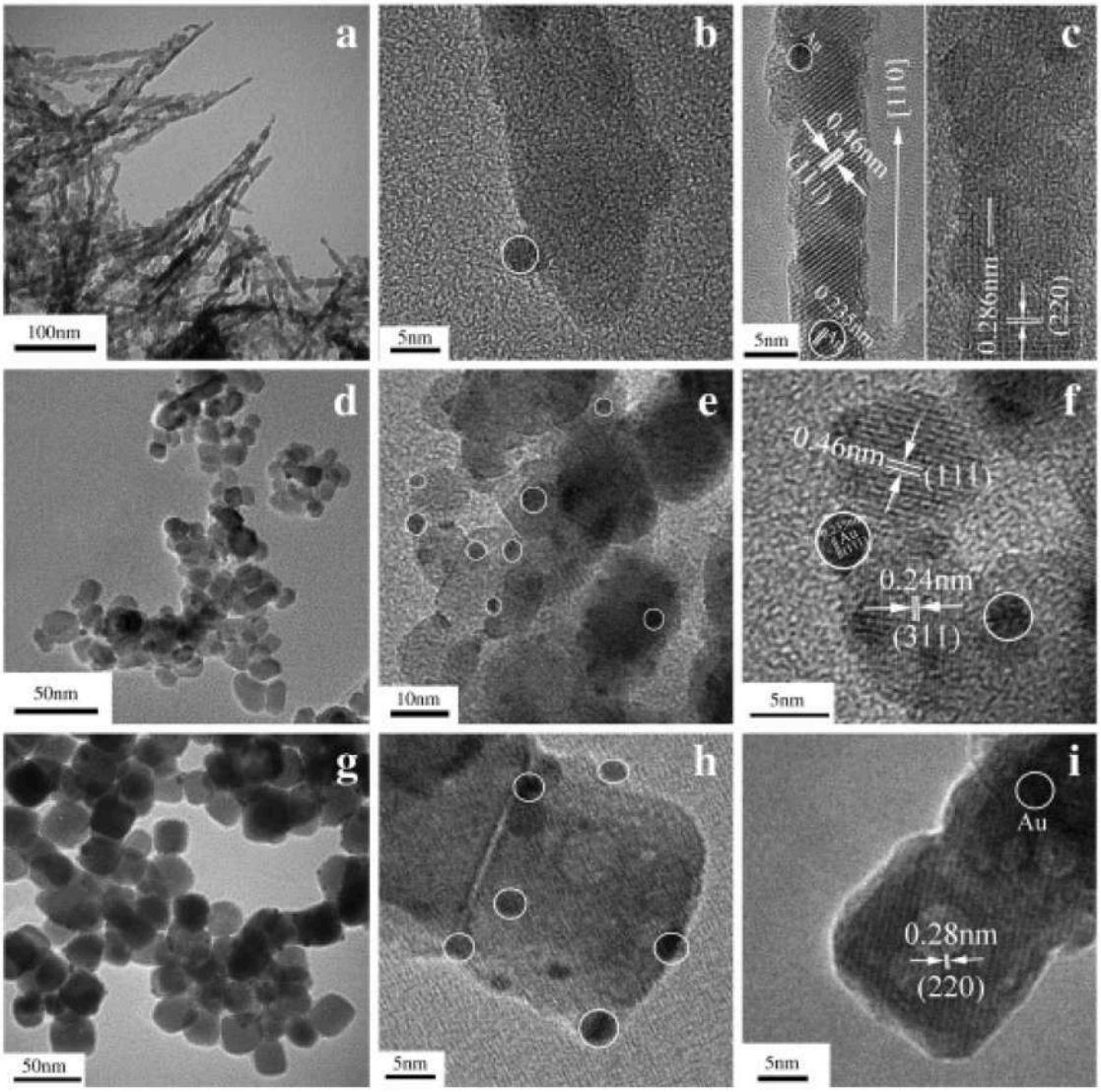


Fig. 12. HRTEM (High Resolution Transmission Electron Microscopy) images of Au/Co_3O_4-nanorods.
(Adapted from Ref. (Xue et al., 2011) Copyright 2011 Elsevier)

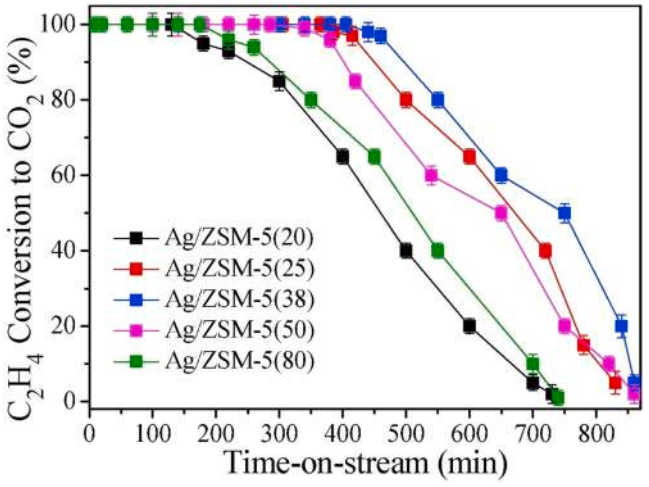


Fig. 13. Reaction tests for ethylene oxidation to CO_2 with time-on-stream over Ag/ZSM-5 catalysts at 25 °C.
(Adapted from Ref. (H. Yang, Ma, Li et al., 2018) Copyright 2018 Elsevier)

exhibit ethylene decomposition activity that were found to effectively reduce ethylene content in packaged tomatoes, as reported by Maneerat and Alizadeh Sani (Maneerat & H, 2008; Alizadeh Sani et al., 2022). Dwivany et al. further explored TiO_2 as a photocatalyst to inhibit fruit ripening, finding that bananas treated with TiO_2 showed an 8-day delay in ripening compared to untreated fruits (Dwivany et al., 2019).

To improve TiO_2's ethylene scavenging efficiency, Nugroho et al. synthesized manganese-loaded TiO_2 by reducing MnO_4 on P25 TiO_2 (Nugroho et al., 2024). This modification enhanced TiO_2's visible light absorption, and the TiO_2/Mn catalyst was able to partially oxidize ethylene to formic acid under visible light. This TiO_2-based material was effective in prolonging the shelf life of artificially ripened bananas by delaying their discoloration, demonstrating its potential in fruit storage systems.

TiO_2-based ethylene scavengers, particularly in packaging materials, show strong potential for reducing ethylene concentrations and delaying fruit ripening. TiO_2's photocatalytic properties and environmental benefits make it an attractive alternative to conventional ethylene scavengers in postharvest storage. Further research into optimizing TiO_2 materials, such as doping with other elements like manganese, will likely improve their commercial viability.

Among various porous materials for ethylene scavenging, zeolites

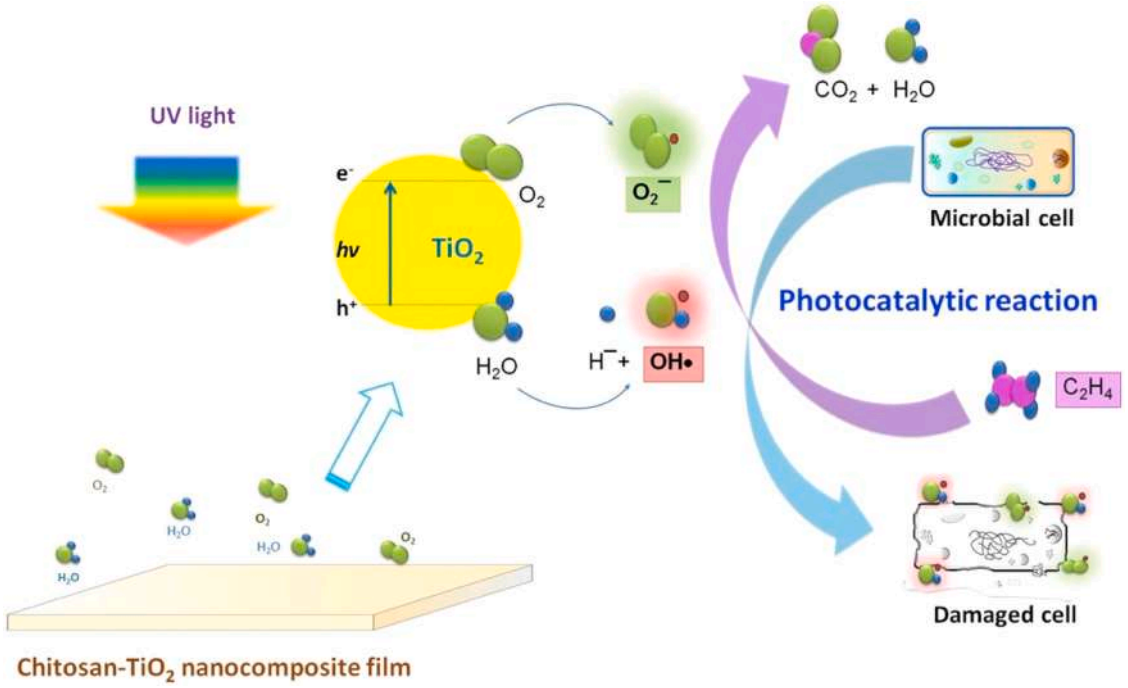


Fig. 14. A schematic diagram of the possible mechanism of photocatalytic degradation of ethylene and antimicrobial activity of the chitosan-TiO_2 nanocomposite film.
(Adapted from Ref. (Siripatrawan & Kaewklin, 2018) Copyright 2018 Elsevier)

are the most commonly used due to their stable structure, large pores, and high surface area (up to 3000 m^2/g) (Álvarez-Hernández et al., 2018; Martínez-Romero et al., 2007; Pereyra et al., 2025). Their porous, three-dimensional structure and cation exchange properties allow zeolites to effectively adsorb ethylene (Table 5) (Yildirim et al., 2017). This makes them particularly suitable for fruit storage, especially under low-temperature or high-humidity conditions.

Zeolite doping with transition metals like copper (Cu^{2+}) and zinc (Zn^{2+}) has gained attention for enhancing ethylene removal (Benaliouche et al., 2012). Copper, in particular, has been shown to increase ethylene adsorption, and when combined with TiO_2, it improves photocatalytic activity. Zinc oxide (ZnO) is also a promising alternative to TiO_2 due to its lower cost. While transition metals have shown positive results in improving ethylene adsorption, further research is needed to fully understand how these metals influence adsorption mechanisms.

Abreu et al. studied Cu^{2+} and Zn^{2+} doping in zeolites, finding that copper-exchanged zeolites exhibited stronger ethylene adsorption due to a higher surface area and stronger ethylene-cation interactions (Abreu et al., 2019). Competitive adsorption of ethylene and water, however, reduced ethylene adsorption efficiency, highlighting the importance of optimizing the surface-active sites of zeolites. Further research on transition metal-doped zeolites, as well as their use in plasma-catalyzed oxidation, could improve the performance of ethylene removal systems in postharvest applications.

Table 5
Adsorption effects of ethylene adsorbents supported by different metals.

Absorbent	Load capacity	Applicable conditions	Ethylene conversion	Ref.
Pt/MCM-41	1 wt %	25 °C or 0 °C	99.8 %	(Jiang et al., 2013)
Pt/SBA-15	1.8 wt %	0 °C	33 %	(S.S. Satter, Yokoya et al., 2018)
Au/Co_3O_4	4 wt %	20 °C	54.89 %	(Jinjun Li et al., 2008)
Au/Co_3O_4	2.5 wt %	0 °C	76 %	(Ma et al., 2009)
Au/Co_3O_4-nanorods	2 wt %	0 °C	93.7 %	(Xue et al., 2011)
Ag/ZSM-5	5 wt %	25 °C	100 %	(H. Yang, Ma, Li et al., 2018)
Ag/SiO_2	5 wt %	25 °C	33 %	(H. Yang, Ma, Li et al., 2018)
$Ag/\alpha\text{-}Al_2O_3$	5 wt %	25 °C	40 %	(H. Yang, Ma, Li et al., 2018)
Ag/MCM-41	5 wt %	25 °C	83 %	(H. Yang, Ma, Li et al., 2018)
Z- Cu/Zn	4.3 wt % Cu 3.3 wt % Zn	20 °C	57 %	(de Bruijn et al., 2020)
Pd-promoted nano zeolite	5 wt %	Common temperature	99.9 %	(Mansourbahmani et al., 2017)
Pd/ZSM-5	0.21 wt %	25 °C	97.4 %	(Saud et al., 2022)

4. Conclusion

This paper reviews emerging ethylene removal technologies that employ both physical adsorption and chemical elimination methods, with a focus on their potential applications within the post-harvesting supply chain and food logistics. The review highlights various catalysts used in these technologies, including catalytic scavengers effective in eliminating ethylene, particularly in the context of fruit and vegetable (F&V) preservation. One of the challenges identified in the use of $KMnO_4$ (potassium permanganate) for ethylene removal is its decreasing efficiency due to saturation over time. This necessitates the frequent replacement of $KMnO_4$, especially in commodities with high ethylene emissions. Additionally, $KMnO_4$ is not typically incorporated into packaging materials that come into direct contact with food because of its high toxicity and the potential for its dark purple color to migrate onto fresh produce. Direct food contact may induce human toxicity and interact with food components, potentially altering color, flavor, and natural aroma. Consequently, such applications are generally avoided in food-contact scenarios.

In contrast, 1-MCP (1-methylcyclopropene) is an effective, low-cost option for fruit and vegetable preservation, with no residue or toxicity concerns. However, 1-MCP has the potential to cause disorders that could lead to disease in a variety of fruits. Despite these drawbacks, emerging catalytic oxidation technologies offer promising alternatives to resolve the limitations associated with traditional ethylene removal methods. Metal catalyst-induced photocatalysis, particularly using TiO_2 (titanium dioxide) and other metal oxide catalysts, has gained significant attention due to their unique properties, high surface area, and industrial applicability. These materials present several advantages for ethylene removal, including their ability to decompose ethylene to harmless byproducts, such as CO_2 and H_2O, when activated by light.

One key advantage of metal or metal oxide catalysts loaded onto porous materials is their enhanced ability to remove ethylene, especially when nanoscale molecular sieves are used. These materials feature a large specific surface area and mesopore volume, allowing them to not only regulate the atmosphere within packaging but also exhibit antibacterial properties, poison resistance, and oxidative ethylene decomposition. As such, they provide an effective means of controlling ethylene levels during the postharvest storage of fruits and vegetables, thus extending their shelf life.

For future developments, greater attention should be focused on making these technologies more cost-effective, leveraging the wide availability of different metal types to load onto molecular sieves. Moreover, adjusting the pore size of the molecular sieves and refining synthesis methods can further optimize their ability to adsorb ethylene. It is also essential to consider the impact of the dry and humid environments on the Brønsted acid sites of catalysts, as moisture can alter their activity. One promising solution is the development of hydrophobic molecular sieves, which can better maintain their ethylene-removal utility in different atmospheric conditions.

Additionally, while metal oxide catalysts show significant potential, their use in packaging films must be carefully evaluated, primarily due to food hygiene concerns and food-related regulations. When designing packaging materials incorporating metal catalysts, it is crucial to consider not only the efficiency of ethylene removal and the preservation of fruit freshness, but also food safety. The materials used must comply with relevant food safety standards to ensure that no harmful substances are transferred to the food products. Thus, future research and development efforts should balance catalytic effectiveness with regulatory requirements and consumer safety.

In summary, while traditional methods like $KMnO_4$ and 1-MCP have their limitations, the development of new catalytic technologies, especially those involving metal oxide catalysts and nanoscale molecular sieves, metal- & polymer- modified zeolite scaffolds, offers exciting possibilities for the effective removal of ethylene in fruit and vegetable preservation. As these technologies continue to evolve, they hold great promise for improving the sustainability and safety of the postharvest supply chain, particularly by addressing both economic and environmental concerns.

Ethical statement

The present manuscript does not contain any studies involving human participants or animals performed by the authors. No ethical approval or informed consent was necessary for this work.

CRediT authorship contribution statement

Yanan Wang: Writing – original draft, Data curation. **Jingfei Xu:** Writing – review & editing. **Rinat M. Iskakov:** Writing – review & editing, Resources, Conceptualization. **Xicheng Jia:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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