© AUG 2026 | IRE Journals | Volume 10 Issue 2 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I2-1722379

Prospects of Ethylene Absorbers in Reducing Postharvest Losses and Extending the Shelf Life of Tomato (Solanum lycopersicum L.) in Nigeria

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Abstract- Tomato moves quickly from harvest to deterioration, especially where fruit is exposed to heat, rough handling, water loss, poor packaging and delays in marketing. Ethylene is part of this process because it drives ripening and softening, but it is not the only cause of loss. This paper examines whether materials that remove ethylene from storage or packaging atmospheres could help preserve tomato in Nigeria. Evidence from original tomato experiments was considered separately from review articles, studies on other crops and treatments such as 1-methylcyclopropene and edible coatings. Modified zeolites, potassium-permanganate systems and promoted porous materials have reduced ethylene or delayed aspects of ripening under controlled conditions. The size of the benefit, however, changes with cultivar, maturity, temperature, humidity, dose, package design and the way shelf life is defined. One Nigerian experiment found that a treatment described as 5% potassium permanganate delayed complete spoilage, although the study did not establish the marketable life, commercial sachet design or cost of the treatment. The available evidence supports further development of ethylene absorbers as part of a broader postharvest system rather than as a stand-alone answer to tomato loss. Their practical value in Nigeria will depend on safe containment, reliable performance in warm and humid conditions, affordability and field testing with traders and farmers.

Keywords: active packaging; ethylene scavenger; potassium permanganate; postharvest loss; tomato; Nigeria; zeolite

I. INTRODUCTION

Tomato is grown across most of Nigeria, but commercial production is concentrated in the northern production belt. Yami et al. (2025) reported that tomato is produced in 33 of the country's 36 states and that Kaduna, Kano and Plateau together contribute more than half of national output. Drawing on National Agricultural Extension and Research Liaison Services data, the same study reported that more than 45,000 ha were cultivated with tomato in Kano State in 2023. Within this production concentration, farmer varietal choice is not uniform: Adeboye et al. (2024) documented the cultivars most preferred by tomato farmers across selected local government areas of Kano State, showing that a small set of varieties dominates the fields that supply distant urban markets. The postharvest performance of these preferred cultivars therefore determines much of what reaches consumers. This concentration links production areas to distant urban markets and makes harvesting, packaging, transport and temporary storage important determinants of the amount and quality of fruit that reaches consumers.

The scale of postharvest loss is substantial, although published values should be treated as estimates rather than as a single national measurement. Yami et al. (2025) summarised studies indicating that approximately 33-50% of Nigerian tomato production may fail to reach markets, principally because of inadequate handling and storage infrastructure. The underlying problem is not one process alone. High temperature accelerates metabolism and water loss; rough handling and unsuitable packaging cause physical injury; and damaged or overripe fruit becomes more susceptible to microbial decay. Cultivar, maturity at harvest and storage conditions also affect how quickly fruit loses marketable quality (Yusuf et al., 2023; Safari et al., 2020).

Ethylene is nevertheless an important part of this deterioration pathway. Tomato is a climacteric fruit and can continue to ripen after harvest through a rise in respiration and autocatalytic ethylene production.

Ethylene coordinates changes associated with ripening, including chlorophyll loss, pigment development and tissue softening, and fresh produce can respond to very low atmospheric concentrations; effects around 0.1 microlitre L-1 have been reported in the broader fruit and vegetable literature (de Bruijn et al., 2020; Alonso-Salinas et al., 2024; Wei et al., 2020). Managing ethylene can therefore slow one important driver of ripening and senescence, but it cannot replace careful harvesting, temperature management, ventilation, hygienic handling and protection from mechanical injury.

Ethylene-management technologies act through different mechanisms and should not be treated as one category. True absorbers or scavengers lower the concentration of ethylene surrounding the produce through adsorption, chemical oxidation or catalytic conversion. Potassium permanganate systems, porous adsorbents such as zeolites and activated carbon, and some photocatalytic materials belong to this group (Sadeghi et al., 2019; Awalgaonkar et al., 2020). By contrast, 1-methylcyclopropene blocks ethylene perception at the receptor and does not remove the gas. Edible coatings act mainly through barrier and antimicrobial effects, although changes in gas exchange may also influence ripening (Pathak and Mahajan, 2017; Peralta-Ruiz et al., 2020). Separating these mechanisms is necessary when treatment performance and practical requirements are compared.

Experimental findings show potential, but they also demonstrate why broad performance claims are unreliable. In tomato stored at 20 degrees C and high relative humidity, copper- and zinc-modified natural zeolite removed 57% of headspace ethylene after eight days and delayed the main ethylene burst by about seven days; unmodified zeolite performed less reliably because water competed for adsorption sites (de Bruijn et al., 2020). In a Nigerian experiment, fruit stored with the treatment described as 5% potassium permanganate reached 100% spoilage after 44.63 and 47.30 days in two trials, compared with 18.25 and 17.88 days for open-shelf controls (Oduntan et al., 2026). These values describe the tested spoilage endpoint under specific experimental conditions; they should not be presented as a universal marketable shelf life. Differences in cultivar, maturity, temperature, humidity, formulation and outcome definition also prevent a defensible pooled percentage for shelf-life extension.

Against this background, the paper considers whether ethylene absorbers can make a useful contribution to tomato handling in Nigeria. The discussion moves from the biology of ripening to the main absorber technologies, then weighs the experimental evidence against the conditions found in Nigerian supply chains. Safety, affordability and ease of use are treated as part of effectiveness, because a material that works only in a tightly controlled laboratory system may offer little value to farmers and traders.

II. SCOPE AND APPROACH OF THE REVIEW

This paper is a focused narrative review of the 29 articles available for the study. The collection contains original experiments, review papers, a policy discussion and a reference chapter. It was not assembled through a formal database search, so the paper does not claim the coverage of a systematic review. Instead, it uses the available literature to examine the strength and limits of the evidence most relevant to tomato and Nigeria.

Studies were included when they dealt with tomato ripening or postharvest quality, ethylene production and action, ethylene-removing materials, related preservation treatments, or conditions in Nigerian tomato markets. Experiments conducted directly on tomato received the greatest weight when shelf life, firmness, colour, weight loss and decay were discussed. Work on mango, broccoli and other produce was used only to explain mechanisms or possible applications; it was not treated as direct proof of performance in tomato.

For each experimental paper, attention was given to the cultivar and maturity stage, treatment formulation and dose, storage temperature and humidity, duration, comparator and definition of the outcome. This made it possible to separate a measured reduction in headspace ethylene from a change in ethylene production, weight loss, decay or time to complete

DOI: https://doi.org/10.64388/IREV10I2-1722379

spoilage. Numerical findings were retained only when their experimental meaning could be established from the article.

The evidence was then grouped by mechanism. Materials that adsorb, oxidise or catalytically remove ethylene were considered separately from 1-MCP, coatings and other treatments that act through different pathways. Results were compared in their original experimental context rather than combined into a single percentage, since the studies varied too widely in treatment, cultivar, package design and definition of shelf life.

The approach has clear limitations. Several studies were conducted under refrigeration or in sealed laboratory containers, and only a small part of the evidence came from Nigerian-grown tomato. The collection may also omit relevant work outside the available articles. The conclusions are therefore framed as a critical reading of the present evidence and as a guide for field testing, rather than as a meta-analysis.

III. TOMATO RIPENING AND ETHYLENE BIOLOGY

3.1 Ripening physiology

Tomato is a climacteric fruit. After physiological maturity, it can continue the transition from mature green through breaker, turning, pink and red stages after harvest. This transition includes chlorophyll degradation, carotenoid accumulation, changes in sugars and organic acids, development of aroma volatiles and progressive softening of the cell wall. Respiration and ethylene production rise around the onset of ripening, after which tissue becomes increasingly susceptible to water loss, bruising and microbial invasion (Alonso-Salinas et al., 2024; Mubarok et al., 2023). The rate of change is not fixed: cultivar, harvest maturity, temperature, atmosphere and prior injury all influence the remaining marketable period.

Softening is particularly important in the tomato supply chain because it reduces resistance to compression and impact. Ethylene-responsive changes in pectin metabolism contribute to loss of firmness, while respiration consumes substrates and transpiration reduces mass. These physiological events can make the fruit easier to damage, but they do not act independently of handling and infection. A bruised fruit may deteriorate rapidly even if headspace ethylene is reduced, and an undamaged fruit may still lose water or develop decay when temperature, sanitation or humidity is poorly controlled.

3.2 Ethylene biosynthesis and perception

Ethylene is synthesised from methionine through S-adenosyl-L-methionine and 1-aminocyclopropane-1-carboxylic acid (ACC). ACC synthase and ACC oxidase control the last two steps of the pathway. In climacteric fruit, the low basal production associated with System I gives way to autocatalytic System II production during ripening, so ethylene exposure can stimulate further ethylene synthesis. Reviews of tomato and other climacteric crops describe this feedback as a central reason why ethylene accumulating in an enclosed package can accelerate otherwise coordinated ripening (Zhang et al., 2017; Cocetta and Natalini, 2022; Alonso-Salinas et al., 2024).

Perception begins when ethylene binds to receptors associated with the endoplasmic reticulum. Downstream signalling releases transcriptional regulators that activate ripening-related genes. Tomato has several ethylene receptors and a broader network of ripening regulators, including RIN, NOR and CNR (Mubarok et al., 2023). This biology creates three distinct intervention points: reduce ethylene biosynthesis, block receptor action, or remove ethylene from the atmosphere around the fruit. Only the third approach constitutes ethylene absorption or scavenging.

3.3 Ethylene within a multi-causal deterioration system

Ethylene management can slow colour development, softening and senescence, but it cannot by itself control every cause of postharvest loss. Temperature affects respiration and microbial growth; relative humidity affects both water loss and the performance of some adsorbents; packaging influences compression, ventilation and gas transfer; and surface injury creates entry points for pathogens. The Nigerian loss problem should therefore be understood as a system in which ethylene-driven ripening interacts with heat, water loss, physical damage, infection and delays in marketing. This distinction prevents laboratory evidence for one physiological mechanism from being converted into an unsupported estimate of national loss reduction.

IV. TYPES AND MECHANISMS OF ETHYLENE-MANAGEMENT TECHNOLOGIES

4.1 Classification of true removers

Ethylene-removal technologies can be classified by their dominant mechanism. Physical adsorbents retain ethylene within pores or on active surfaces. Chemical oxidisers convert the gas into other compounds. Catalytic and photocatalytic systems promote oxidation, sometimes with light or airflow requirements. The active material may be supplied in a sachet, filter, pad, film or separate cartridge. Ventilation can also lower ethylene concentration, although it is a storage-management practice rather than an active absorber (Pathak and Mahajan, 2017; Awalgaonkar et al., 2020; Sadeghi et al., 2019).

Performance depends on more than the name of the active ingredient. The quantity of fruit, ethylene-production rate, headspace volume, package permeability, temperature, relative humidity, active-material loading, surface area and placement all influence whether the remover can keep pace with ethylene generation. Capacity and reaction rate are also different properties: a material may remove ethylene quickly but become exhausted early, or react slowly while retaining useful capacity over a longer period (Awalgaonkar et al., 2020).

4.2 Potassium permanganate systems

Potassium permanganate ($KMnO_4$) is widely discussed as an oxidising ethylene scavenger. It is normally immobilised on a porous carrier or enclosed within a gas-permeable sachet so that ethylene can reach the oxidant without the chemical touching the fruit. Reviews describe oxidation through intermediate products to carbon dioxide and water, accompanied by reduction of permanganate and a visible change from purple towards brown. The colour change can indicate consumption of active oxidant, but it does not replace a measured capacity or replacement schedule (Wei et al., 2020; Sadeghi et al., 2019).

$KMnO_4$ should not make direct food contact because of its toxic and caustic properties. Carrier chemistry, active loading, humidity and package design affect performance. The 3-6% value reported in some reviews concerns a carrier-solubility or formulation limitation and should not be treated as a universal commercial loading standard (Awalgaonkar et al., 2020). Similarly, the 5% treatment in Oduntan et al. (2026) was prepared as 5 g in 100 mL of distilled water placed next to the fruit; it was not described as a commercial sachet or as 5% $KMnO_4$ impregnated into a carrier.

4.3 Porous adsorbents and promoted materials

Activated carbon, zeolites and selected clays offer high internal surface area and can adsorb ethylene. Their advantages include relatively simple formats and the possibility of combining adsorption with an oxidising or catalytic promoter. Their limitations include non-specific adsorption, finite capacity and competition from water and other volatile compounds. High relative humidity is especially important for tomato because water may occupy sites that would otherwise retain ethylene (Gaikwad et al., 2020; Awalgaonkar et al., 2020).

Metal modification can strengthen the interaction between ethylene and a porous material. In tomato, copper- and zinc-modified natural zeolite outperformed the unmodified material under the conditions tested by de Bruijn et al. (2020). Mansourbahmani et al. (2018) also reported strong performance from palladium- and $KMnO_4$-promoted nano-zeolites during refrigerated storage. These findings support formulation-specific evaluation; they do not establish that all natural zeolites, activated carbons or clays are effective without characterisation and testing.

4.4 Catalytic, photocatalytic and emerging systems

Titanium dioxide can oxidise ethylene photocatalytically when appropriate light, oxygen and surface conditions are available. Palladium and other metals can promote adsorption or catalytic conversion at relatively low loadings. These approaches may offer stronger or more humidity-tolerant performance than an unmodified adsorbent, but they introduce questions about light or airflow requirements, material cost, migration, recovery and food-contact approval (Awalgaonkar et al., 2020; Gaikwad et al., 2020).

Evidence from another commodity may clarify mechanism without proving tomato efficacy. For example, Alonso-Salinas et al. (2023) evaluated $KMnO_4$, ultraviolet radiation and titanium dioxide in preserving broccoli stored with tomatoes as the ethylene source. The measured preservation outcome concerned broccoli, not tomato. Such work can inform system design but should not be counted as a tomato shelf-life experiment.

4.5 Technologies that manage ethylene without removing it

1-Methylcyclopropene (1-MCP) occupies ethylene receptors and reduces tissue response to the hormone. Its efficacy therefore depends on exposure conditions, maturity and the ability of the fruit to form new receptors; it does not reduce headspace ethylene by adsorption or oxidation (Pathak and Mahajan, 2017; Boggala et al., 2015). Edible coatings form barriers to water and gas transfer and may deliver antimicrobial agents. They can alter respiration or ethylene production indirectly, but the coating studies reviewed here did not demonstrate direct scavenging of ethylene (Safari et al., 2020; Peralta-Ruiz et al., 2020). These treatments are retained as comparators or possible components of an integrated preservation system.

V. EVIDENCE FROM TOMATO STUDIES

The tomato studies in the reviewed corpus cannot be reduced to one pooled treatment effect. They differ in cultivar and harvest maturity, temperature, relative humidity, treatment format, exposure period and outcome definition. Some measured headspace ethylene directly, whereas others measured weight loss, decay, firmness, colour or time to complete spoilage. The evidence is therefore synthesised by mechanism and experimental context rather than combined into a single percentage for shelf-life extension.

Table 1. Comparison of the principal tomato studies used in the evidence synthesis

Study	Mechanism	Storage conditions	Main verified result	Main limitation
de Bruijn *et al*. (2020)	Cu/Zn-modified zeolite; direct removal	Medano, breaker stage; 20 °C; 88% RH; 15 d	57% ethylene removal at day 8; main ethylene burst delayed about 7 d	Small sealed units; adsorption weakened under high humidity and later storage
Mansourbahmani *et al*. (2018)	Pd- and $KMnO_4$-promoted nano-zeolites; direct removal	Valouro, red stage; 7 ± 0.5 °C; 90 ± 2% RH; 35 d	At day 7, 5% Pd kept measured ethylene near zero versus 10.33 µL kg-1 h-1 in control	Cold laboratory storage; cost, safety and scale-up were not assessed
Oduntan *et al*. (2026)	$KMnO_4$, zeolite and 1-MCP; mixed design	Beske, breaker stage; treatment at 25 °C and 85-90% RH; stored to spoilage	5% $KMnO_4$ reached 100% spoilage at 44.63 and 47.30 d versus 18.25 and 17.88 d for open shelf	Fertiliser and treatment effects were combined; endpoint was complete spoilage

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DOI: https://doi.org/10.64388/IREV10I2-1722379

Zakriya *et al*. (2023)	KMnO4 sachet plus 2% $CaCl_2$	Roma, mature-green/breaker; ambient conditions; 30 and 40 d	Day-40 weight loss was 6.86% versus 17.93% in untreated fruit	Combination confounds CaCl2 and KMnO4; temperature and RH were not quantified
Boggala *et al*. (2015)	Aqueous 1-MCP; receptor inhibition	Punjab Ratta; 13 ± 2 °C; 85-90% RH; 26 d	Day-26 decay was 9.87% with 120 mg/10 L versus 35.65% in control	Not an absorber; abstract and table differ on the best late weight-loss dose

Source: synthesis of the cited studies. Results are retained with their original treatments, comparators and endpoints; they are not pooled.

5.1 Direct evidence for ethylene removal

The clearest mechanistic evidence is provided by de Bruijn et al. (2020), who stored breaker-stage Medano tomatoes in sealed 10-L containers at 20 °C and 88% relative humidity. Each experimental unit contained approximately 0.75 kg of fruit and either no material, 10 g of natural zeolite or 10 g of copper- and zinc-modified zeolite. After eight days, ethylene concentration had been reduced by 57% with the modified zeolite and by 37% with the natural zeolite. The pronounced ethylene increase observed in the control at about 2.5 days occurred at about 9.5 days in the zeolite treatments, which represents a delay of approximately seven days rather than a 9.5-day extension of shelf life.

This experiment also identifies an operational limit. Water competes with ethylene for adsorption sites, and the authors concluded that unmodified zeolite should be used cautiously under high-moisture conditions because it did not control ripening consistently. Ethylene concentrations later increased as the sorption sites approached saturation. The study therefore supports a modified zeolite under the tested loading and headspace conditions, but it does not show that any quantity of ordinary zeolite will remain effective throughout commercial storage.

Mansourbahmani et al. (2018) compared palladium-promoted nano-zeolite, KMnO4-promoted nano-zeolite, 1-MCP, calcium chloride, salicylic acid and UV-C in Valouro tomatoes. The selected levels were 5% palladium-promoted zeolite, 20% KMnO4-promoted zeolite, 30 ppm 1-MCP, 2% calcium chloride, 1% salicylic acid and 15 minutes of UV-C. Fruit were held at 7 ± 0.5 °C and 90 ± 2% relative humidity for 35 days. At day 7, measured ethylene was near zero in the 5% palladium treatment and 10.33 μL kg-1 h-1 in the control. The reported performance order was palladium, KMnO4, 1-MCP, salicylic acid/calcium chloride and UV-C.

The palladium treatment also retained firmness and moderated changes in phenolic content, weight loss and cell-wall enzyme activity. These results strengthen the case for promoted porous materials, yet they are not directly interchangeable with those of de Bruijn et al. (2020). The studies used different cultivars, maturity stages, storage temperatures, material chemistries, and experimental units. In particular, the refrigerated storage used by Mansourbahmani et al. already suppresses metabolic activity. The incremental benefit of the scavenger under warm distribution conditions must therefore be established separately.

5.2 Removal treatments in mixed or combination designs

Oduntan et al. (2026) provide the most directly relevant Nigerian experiment. Beske tomatoes harvested at breaker stage were produced under four fertiliser regimes and then exposed to seven ethylene-remediation treatments: 0.1, 0.3 and 0.5 μL L-1 1-MCP; 5% and 10% KMnO4; and 10 and 20 g of zeolite. An open shelf served as the control. The reported 5% KMnO4 treatment was a solution prepared by dissolving 5 g of KMnO4 in 100 mL of distilled water and placing it next to the fruit. It was not a stated carrier loading or a commercial impregnated sachet.

In two experiments, fruit associated with the 5% $KMnO_4$ treatment reached 100% spoilage after 44.63 and 47.30 days, compared with 18.25 and 17.88 days for open-shelf fruit. The same treatment also delayed the onset and 50% incidence of spoilage. These are substantial treatment differences within the experiment, but the figures describe time to complete spoilage. Fruit may cease to be saleable before all samples are spoiled, so the values should not be restated as 45-47 days of marketable shelf life. Interpretation is further complicated because preharvest fertiliser regime and postharvest treatment were both varied.

Zakriya et al. (2023) evaluated mature-green Roma tomatoes in corrugated cartons under ambient storage. The most effective reported treatment combined a 2% calcium chloride dip with a 50 g $KMnO_4$ sachet. After 40 days, physiological weight loss was 6.86%, compared with 17.93% in untreated fruit, and the treated fruit retained higher measured phenolic, flavonoid, and vitamin C contents. This study supports a combination strategy, not the isolated effect of $KMnO_4$. Calcium chloride can influence firmness and membrane stability, while the sachet is intended to remove ethylene. Because there was no $KMnO_4$-only arm paired with the same pretreatment, the contribution of each component cannot be separated. The paper also described storage only as ambient and did not report a numeric temperature or relative humidity.

5.3 Evidence from 1-MCP treatments

1-MCP is relevant to ethylene management but is not an absorber. It binds to ethylene receptors and temporarily reduces tissue sensitivity to the hormone; it does not adsorb or oxidise ethylene in the storage atmosphere. This distinction matters when efficacy, worker exposure, treatment equipment and regulatory requirements are compared.

Boggala et al. (2015) dipped Punjab Ratta tomatoes in aqueous 1-MCP at 60, 120 or 180 mg per 10 L and stored them at 13 ± 2 °C and 85-90% relative humidity for 26 days. At the final assessment, the 120 mg per 10 L treatment produced 9.87% decay, compared with 35.65% in the water-dipped control. The article's abstract states that 180 mg per 10 L produced the lowest physiological weight loss throughout storage, but Table 2 reports lower values for 120 mg per 10 L at days 21 and 26. The decay result is clear; the late weight-loss ranking should be described with this internal inconsistency noted.

Ruiz-Aracil et al. (2024) combined 0.5 µL L^{-1} 1-MCP with a 10 mM gamma-aminobutyric acid (GABA) dip in Conquista tomatoes. Fruit were stored for 21 days at 4 °C and 90% relative humidity, followed by seven days at 20 °C. The combined treatment produced the lowest chilling injury and rot incidence, maintained the highest firmness, and reduced ethylene production by about half at the end of storage relative to the control. This is evidence for a combined cold-chain treatment: the result cannot be attributed to 1-MCP alone, and lower ethylene production by the fruit is not the same as removal of ethylene from the surrounding air.

5.4 Coatings and other complementary preservation treatments

Three tomato experiments demonstrate useful preservation effects from edible coatings. Safari et al. (2020) stored pink-stage Syngenta 1039 tomatoes at 26 ± 2 °C and 60 ± 5% relative humidity for 25 days. A coating containing 1.5% chitosan and 15 mM vanillin reduced disease incidence by 74.16% and disease severity by 79%, while the authors reported a delay in weight loss of up to 90%. The coating also moderated respiration and ethylene production. Its principal functions were barrier formation and antimicrobial protection rather than removal of ethylene from the package atmosphere.

Peralta-Ruiz et al. (2020) applied a 2% chitosan coating containing Ruta graveolens essential oil to Chonto tomatoes stored at 4 ± 0.2 °C for 12 days. At the highest oil concentration, day-12 weight loss was 16.7%, compared with 29.8% in uncoated fruit, and the decay index was 1.0 rather than 3.0. Salas-Méndez et al. (2019) used five alternating alginate and chitosan nanolayers containing Flourensia cernua extract. At 20 °C and 85% relative humidity, coated tomatoes with the extract lost 3.8% of their weight after 15 days, compared with 9.8% for uncoated fruit, and had the lowest measured ethylene production. Both studies show that coatings can reduce water transfer, respiration and microbial deterioration. Neither demonstrates that the coating scavenged ethylene.

Coatings may still be valuable in an integrated system. An absorber can only address ethylene accumulating around the fruit; it cannot restore moisture, prevent physical injury or directly control every spoilage organism. A coating may reduce water loss and surface infection while an absorber controls headspace ethylene. However, these effects should not simply be added together. Coatings alter gas exchange and may change the amount and timing of ethylene entering a package, so combined systems require direct testing for oxygen, carbon dioxide, humidity, off-odours, ripening and food-contact safety.

5.5 Nigerian plant-based preservation evidence

Ugwu et al. (2024) assessed wood ash, sawdust and moringa leaf powder as low-cost preservatives for Roma VF, Ogbomosho local and Ibadan local tomatoes in Enugu State. Each paper carton contained 400 g of one preservative, and fruit were observed at room temperature for 28 days. Across the varieties, moringa leaf powder produced the longest reported mean time to complete decay, 26 days, compared with 21 days for sawdust and 20 days for wood ash. Untreated controls reached complete spoilage after 9-14 days, depending on variety. Roma VF lasted longest overall.

The sensory result was different from the spoilage result: sawdust-treated tomatoes received the highest ratings for appearance, aroma, texture and general acceptability. It is therefore inaccurate to identify one material as best without naming the outcome. Moringa performed best for time to complete decay, while sawdust performed best in the sensory assessment. Because the study did not measure ethylene concentration or verify an adsorption or oxidation mechanism, none of the three materials should be described as a confirmed ethylene absorber based on this experiment.

VI. COMPARATIVE INTERPRETATION OF TREATMENTS

6.1 Why the reported outcomes are not interchangeable

The studies use several outcomes that answer different questions. Headspace ethylene removal measures the performance of the material. Ethylene production measures the fruit's physiological response. Weight loss mainly reflects transpiration and respiratory mass loss. Firmness and colour describe ripening, while decay may reflect microbial infection as well as tissue senescence. Time to 100% spoilage records the point at which all fruit are affected, not the earlier point at which a trader or consumer would reject the lot. These endpoints can support a coherent explanation of treatment effects, but they cannot be substituted for one another.

This is why a general claim that ethylene absorbers extend tomato shelf life by 50-150% or reduce weight loss by 30-60% is not defensible from the reviewed corpus. Such ranges would combine different mechanisms, doses, storage conditions, maturity stages and definitions of shelf life. A more accurate synthesis reports the treatment-specific result and then examines whether the conditions resemble the supply chain in which the technology is intended to operate.

6.2 Factors that explain variation between studies

Much of the variation between studies can be explained by the way the experiments were run. Refrigeration slows respiration and microbial growth, whereas high humidity may occupy adsorption sites in zeolites. Breaker-stage fruit, pink fruit and red-ripe fruit also have different ethylene production rates and remaining storage lives. Formulation matters as well: a 5% $KMnO_4$ solution, $KMnO_4$ held on zeolite and a 50 g $KMnO_4$ sachet are not equivalent products. Their active mass, surface area, containment and useful capacity differ, just as the amount of fruit, container volume, ventilation and choice of control differ between experiments.

6.3 Conclusions supported by the reviewed evidence

Taken together, the studies show that modified zeolites and promoted porous materials can reduce

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DOI: https://doi.org/10.64388/IREV10I2-1722379

headspace ethylene and delay some ripening responses under controlled conditions. Oduntan et al. (2026) also show that the treatment described as 5% $KMnO_4$ delayed complete spoilage relative to an open shelf in a Nigerian experiment. At the same time, the evidence remains conditional on temperature, humidity, cultivar, maturity, dose, container design and the endpoint used to define shelf life.

6.4 Claims not supported by the reviewed evidence

The same literature sets important boundaries. It does not establish one percentage improvement that applies to every absorber, and it does not show that ethylene is the main cause of most Nigerian tomato losses. It also gives no basis for automatically classifying ordinary zeolite, sawdust, wood ash or moringa powder as validated ethylene absorbers. Findings from mango, broccoli or another commodity may suggest a mechanism, but their efficacy values cannot be transferred directly to tomato.

6.5 Evidence gap carried forward to the Nigerian assessment

The evidence supports further evaluation rather than immediate claims of large-scale commercial readiness. The central gap is a field-relevant comparison under Nigerian conditions using defined absorber formulations, locally important cultivars, realistic crate or carton loadings, warm and humid storage, and outcomes based on marketability as well as spoilage. Such studies should measure headspace ethylene, temperature, relative humidity, weight loss, firmness, colour, decay, sensory quality, active-material capacity and the cost per kilogram of fruit protected. Safety, containment and disposal must be assessed for $KMnO_4$ systems. These requirements provide the basis for the subsequent evaluation of applicability, economics and regulation in Nigerian supply chains.

VII. APPLICABILITY TO NIGERIAN TOMATO SUPPLY CHAINS

7.1 Operating conditions and intervention fit

The Nigerian tomato chain links concentrated production zones in the north with distant wholesale and urban markets. Yami et al. (2025) identified inadequate packaging, storage and handling as part of a wider set of postharvest constraints. Under warm conditions, respiration, ethylene production and water loss proceed quickly, while raffia baskets and repeated handling can expose fruit to compression and impact. An ethylene absorber would address only the gaseous component of this system. Its effect would be greatest where fruit are held in a container or storage space that retains enough ethylene for removal to matter but still maintains safe oxygen and carbon dioxide levels.

Open display and highly ventilated transport may provide too little controlled headspace for a small sachet to influence the atmosphere consistently. Conversely, a tightly sealed package may create oxygen depletion, carbon dioxide accumulation, condensation or off-odours if its permeability is poorly matched to fruit respiration. Deployment therefore requires a package-level design rather than simply placing an unspecified amount of absorbent beside a crate. Fruit load, package volume, ventilation, journey time and likely temperature should determine the material quantity and replacement schedule (Awalgaonkar et al., 2020).

7.2 What the Nigerian experiments establish

Oduntan et al. (2026) demonstrate that ethylene-remediation treatments can alter the spoilage trajectory of Nigerian-grown tomato under laboratory conditions. The reported 5% $KMnO_4$ treatment substantially delayed the point of complete spoilage relative to an open shelf. However, the study does not establish a commercial sachet specification, cost per crate, safe handling procedure or marketable-life endpoint. It should be treated as evidence that justifies field development, not as proof that the same numerical result will occur across cultivars, seasons and transport routes.

Ugwu et al. (2024) provide separate evidence that locally accessible plant and wood materials can influence spoilage and sensory outcomes. Moringa leaf powder produced the longest mean time to complete decay, whereas sawdust gave the strongest sensory ratings. Because ethylene was not measured, the materials cannot yet be classified as ethylene absorbers. Their practical value, dust generation,

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DOI: https://doi.org/10.64388/IREV10I2-1722379

microbial status, food contact and mode of action require separate study.

7.3 Integration with handling, packaging and cooling

The most defensible application is an integrated system. Fruit should be harvested at an appropriate maturity, shaded promptly, sorted to remove damaged samples and packed in containers that reduce compression. Low-cost cooling or temperature management can slow respiration, while sanitation and coatings may reduce infection or water loss. An absorber can then be evaluated for additional control of headspace ethylene. The components must be tested together because cooling changes ethylene production, coatings change gas exchange, and package ventilation changes the concentration reaching the absorber.

Adoption evidence for reusable plastic crates offers a useful but limited analogy. Yami et al. (2025) found that rural unavailability, ownership cost and weak market incentives constrained crate adoption, while association membership was positively associated with uptake. These results concern crates rather than absorbers, so they do not establish absorber demand. They do suggest that a technically effective product may still fail if it is unavailable near production areas, must be purchased entirely by farmers, or does not deliver a quality benefit recognised by buyers.

7.4 Local-material opportunities are hypotheses, not established products

Agricultural residues and mineral carriers may provide routes to lower-cost formulations, but local availability and manufacturing feasibility must be demonstrated rather than assumed. Chanka et al. (2024) produced a $KMnO_4$-impregnated silica-alumina from sugar-cane bagasse ash and achieved complete removal of an initial 400 microlitre L^{-1} ethylene concentration within 120 minutes using the 4% formulation in a sealed laboratory flask. The fruit trial was conducted on mango in Thailand. The study establishes a material concept, not the cost, safety or efficacy of a Nigerian tomato product.

A Nigerian development programme would need to characterise any proposed ash, carbon, clay or zeolite feedstock for composition, pore structure, contaminants, moisture response and batch consistency. It would then need to specify active loading, sachet permeability, containment strength, ethylene capacity and shelf stability. Only after those steps should a locally sourced formulation be described as commercially feasible.

VIII. SAFETY, ECONOMIC AND REGULATORY CONSIDERATIONS

8.1 Food-contact and chemical safety

$KMnO_4$-based systems require physical containment. Reviews state that the oxidant should not contact food directly and that toxicity, caustic handling and spent residue must be considered in package design (Sadeghi et al., 2019; Pathak and Mahajan, 2017). A commercial design should prevent leakage during transport, resist puncture and clearly distinguish the sachet from edible contents. Replacement and disposal instructions should reflect the actual formulation and reaction products rather than relying only on a visible colour change.

Other systems also require material-specific assessment. Nanomaterials and metal-promoted adsorbents raise questions about migration and recovery; photocatalytic systems must control exposure to light sources and reactive species; and plant powders or coatings require microbiological and compositional quality control. Regulatory status cannot be transferred automatically between countries, commodities or package formats. The conflicting statements in reviews about 1-MCP residue and organic use illustrate why current product-specific rules should be checked rather than repeated as a universal claim (Pathak and Mahajan, 2017; Wei et al., 2020).

8.2 Economic assessment

The supplied studies do not provide a Nigerian commercial cost for absorber use. A credible economic analysis should calculate the material, sachet, labour, quality-control, packaging, replacement and disposal costs per kilogram of tomato protected. Benefits should be based on marketable fruit sold, not only on delayed complete spoilage in the laboratory. The analysis should also record whether improved quality changes the sale price, reduces rejected loads or merely shifts the timing of loss.

Cost and responsibility may be distributed across farmers, transporters, wholesalers and retailers. Yami et al. (2025) found that reusable-crate acquisition costs and rural availability affected adoption; the reported crate price changed from USD 2.51 before 2021 to USD 5.90, then USD 9.51 in 2022, before falling to USD 7.36 in mid-2023. These figures are not absorber prices, but they show why affordability should be evaluated with dated local prices and realistic ownership or service models.

8.3 Regulatory and quality-control needs

Before market introduction, developers should identify the Nigerian requirements that apply to active food packaging, chemical handling, labelling, worker exposure, transport and waste disposal. Evidence should include the identity and purity of the active material, migration or leakage testing, intended food-contact conditions, capacity and replacement limits, packaging integrity and disposal instructions. Yusuf et al. (2023) emphasised regulated introduction and safety assessment for extended-shelf-life tomato technologies in Nigeria; the same precaution is relevant to absorber products even though their regulatory pathway may differ from that of plant varieties or biological interventions.

Standardisation is also necessary for meaningful comparison. A label such as '5% $KMnO_4$' is incomplete unless it states whether the value refers to solution concentration, carrier loading or another basis. Product documentation should specify active mass, carrier, package permeability, rated ethylene capacity, recommended fruit and headspace loading, operating temperature and humidity, shelf life before use, replacement signal and safe end-of-life procedure.

IX. RESEARCH GAPS AND PRIORITIES

9.1 Field-relevant efficacy trials

The immediate priority is a controlled comparison under representative Nigerian supply-chain conditions. Trials should include locally important cultivars harvested at a defined maturity stage, realistic crate or carton loads, monitored warm and humid conditions and routes of commercially relevant duration. The choice of test cultivars should be informed by documented farmer preferences in the major production zones rather than by researcher convenience. Adeboye et al. (2024), in a survey of selected local government areas of Kano State, identified the tomato varieties most widely adopted by farmers in that region, providing an empirical basis for selecting genotypes whose postharvest behaviour under absorber treatments would be most relevant to national supply. Each treatment should be compared with the same package without an absorber and, where feasible, with improved packaging or cooling alone. Replication should occur across seasons and production locations.

Outcomes should include headspace ethylene, temperature, relative humidity, oxygen, carbon dioxide, weight loss, firmness, colour, decay, sensory acceptability and the proportion of fruit that remains marketable. First rejection, partial spoilage and complete spoilage should be reported separately. Recording only the last point at which all fruit are spoiled can overstate the period during which a trader could sell the lot.

9.2 Formulation, capacity and safety

Candidate formulations should be characterised for ethylene-removal rate and total capacity across the expected temperature and humidity range. Tests should determine whether water, dust or volatile compounds interfere with performance and whether active material migrates or leaks after vibration, compression and repeated handling. $KMnO_4$ systems require explicit containment and disposal studies; regenerated adsorbents require confirmation that performance and safety are retained over repeated cycles.

9.3 Techno-economic and adoption research

Field efficacy should be linked to a partial-budget or value-chain analysis. The relevant unit is the cost per kilogram of marketable tomato delivered, including packaging and handling changes needed for the absorber to function. Studies should identify which actor pays, which actor receives the benefit, whether buyers recognise the quality gain, and whether farmer groups or service providers can reduce access barriers. Awareness and willingness to use ethylene absorbers among Nigerian value-chain actors have not been established by the reviewed studies and should be measured directly rather than inferred from crate adoption.

9.4 Evidence synthesis and reporting standards

Future reviews would benefit from a documented database search, duplicate screening and a predefined extraction protocol. Primary experiments should report cultivar, maturity, fruit mass, headspace volume, package permeability, treatment loading, temperature, relative humidity, replication and the exact definition of shelf life. These details would make it possible to compare studies more reliably and, if sufficient compatible data become available, to conduct a formal quantitative synthesis.

9.5 Moving from laboratory evidence to practical use

A useful development programme would move in stages. The first stage would establish how much ethylene a candidate material can remove at the temperatures and humidity normally encountered after harvest. The next would place the material in a realistic crate, carton or storage enclosure and ask whether the atmosphere around the fruit actually changes. Only then would it make sense to run transport and market trials. At every stage, an absorber should be compared with the same package without the active material. Improved packaging and temperature management should also be tested separately, so that the additional contribution of ethylene removal is visible rather than assumed.

The work would benefit from collaboration among horticultural researchers, packaging specialists, food-safety laboratories, local manufacturers and the people who handle tomato each day. Farmers and traders can identify where fruit is held long enough for ethylene control to matter, while buyers can help define the point at which softness, colour or decay makes a consignment unacceptable. Those practical decisions are as important as the removal capacity measured in a laboratory. They determine whether a sachet or cartridge can be placed safely, replaced at the right time and paid for by an actor who receives a clear benefit.

X. CONCLUSION

Ethylene-removing technologies have a scientifically credible role in tomato postharvest management. Modified zeolites, $KMnO_4$ systems and promoted porous materials have reduced ethylene or delayed selected ripening and spoilage outcomes in controlled tomato experiments. The Nigerian experiment by Oduntan et al. (2026) adds locally relevant evidence, but its time-to-complete-spoilage values should not be treated as a universal marketable shelf life or as a ready commercial specification.

The review also shows the limits of the evidence. Studies differ in cultivar, maturity, temperature, humidity, formulation, package design and endpoint. 1-MCP, coatings, calcium chloride, GABA and plant powders can preserve quality through other mechanisms but should not be counted as direct proof of ethylene removal. The available literature does not support a universal 50-150% extension of tomato shelf life, nor does it show that ethylene is responsible for most Nigerian tomato loss.

For Nigeria, absorbers are best considered as one part of an integrated system that also addresses harvest maturity, mechanical protection, sanitation, ventilation and temperature. Progress towards adoption requires field-relevant formulation tests, food-contact and disposal safeguards, standardised performance reporting, techno-economic analysis and direct study of user acceptance. Until those gaps are resolved, the evidence supports cautious development and validation rather than claims of immediate large-scale readiness.

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