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Emerging smart packaging materials and technologies for ethylene detection and freshness monitoring in fresh produce

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Climacteric fruits and vegetables, such as bananas, mangoes, and kiwis, produce ethylene gas during ripening, which accelerates senescence and spoilage, contributing to major post-harvest losses of fresh produce. Therefore, monitoring and regulating ethylene levels are critical for maintaining freshness and reducing waste in supply chains. This review article explores the emerging technologies in smart packaging for freshness monitoring and real-time ethylene detection. Ethylene biosynthesis for fruit growth and ripening and analytical methods such as gas chromatography, flame ionization, nondispersive infrared technology, and photoacoustic spectroscopy for ethylene detection are discussed. Recent developments in smart packaging such as indicators, sensors, and RFID technology and their working mechanism, manufacturing procedures, and applications for ethylene monitoring during storage and distribution are explored. It is expected that smart packaging of fruits and vegetables will contribute to real-time ethylene detection, freshness indication, and shelf-life extension of produce. Recent innovations in optical sensors, colorimetric indicators, nanomaterial-based films, and RFID-enabled systems offer cost-effective, portable, and responsive solutions for freshness monitoring of fruits. Future research and development will contribute to the integration of the ethylene sensor with blockchain and IoT for multiple spoilage detection and portable smart packaging devices for real-time ethylene monitoring and reducing post-harvest losses.

Sustainability Spotlight

The global challenge of food waste, especially of fruits and vegetables, demands a sustainable solution to extend the shelf life, reduce deterioration, and use less energy for preservation. This review highlights the sustainable smart packaging technologies that enable real-time ethylene detection and freshness monitoring, which promote post-harvest waste minimization. Development of low-cost ethylene detection materials, including indicators, sensors, and RFIDs reduces high energy resource utilization, enhances consumer's experience, and allows for the control of ethylene. This review provides a critical analysis of ethylene's role in the ripening and deterioration of fresh produce, the development of smart packaging materials, and their applications in real-time quality monitoring. This review aligns with the United Nations Sustainable Development Goals, providing safe food consumption, reducing food waste, and providing supply chain transparency globally.

1. Introduction

Fruits and vegetables are rich sources of vitamins, proteins, and phytochemicals, which are essential to the human body for growth. Fresh fruits and vegetables are in demand among consumers.[1] Poor handling and storage lead to the premature ripening and deterioration of these fresh produce commodities. According to the Food and Agriculture Organization (FAO), 40–50% of total fresh produce gets wasted or deteriorated, which is globally 1.3 billion tonnes annually.[2] Climacteric fruits and vegetables are more susceptible to deterioration due to ethylene emission and continuous respiration after harvesting. Bananas, mangoes, peaches, avocados, pumpkins, melons, pears, and apples face the challenge of over-ripening due to excessive ethylene production, which results in browning, loss of nutrients, degradation of texture, and microbial spoilage, contributing to significant post-harvest losses.[3]

Ethylene (C_2H_4) is a plant hormone responsible for the growth and development of fresh produce. Ethylene is a hydrocarbon made up of two double-bonded carbon atoms and four hydrogen atoms, having a colorless and sweet musky odor.[4] Ethylene plays a vital role in the development of the color, taste, and flavor of fruits and vegetables. Postharvest of fresh produce, ethylene emission accelerates the rate of ripening, which causes discoloration, softening, and decay of commodities before

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reaching the consumer.[5] Ethylene quantification in packaging headspace is crucial for maintaining the freshness of fruits and vegetables, which will help optimize storage conditions, reduce post-harvest loss, and ensure the quality of produce during the supply chain.[6] The accumulation of excess ethylene within the packaging environment accelerates ripening, increases the respiration rate, and leads to moisture loss and nutrient degradation. Ethylene-sensitive fresh produce, mainly green vegetables, bananas, mangoes, *etc.*, deteriorates and gets affected by cross-contamination.[7] Conventional analytical techniques for ethylene determination such as gas chromatography (GC), flame ionization detection (FID) or thermal conductivity detection (TCD), photoacoustic spectroscopy (PAS), laser-based spectroscopy method, and cavity ring-down spectroscopy are available. These methods of ethylene detection and freshness monitoring of fruits and vegetables are highly accurate and expensive.[8] A study conducted by Popa *et al.* (2019) used laser-based photoacoustic spectroscopy (PAS) to identify ethylene in cherry, apple, and strawberry flowers under nitrogen and synthetic air flows. The results showed significantly lower ethylene levels under nitrogen flow than under synthetic air flow, with apple flowers emitting 75 ppb (N_2) *vs.* 131 ppb (synthetic air), strawberry flowers emitting 20 ppb *vs.* 40 ppb, and cherry flowers emitting 56 ppb *vs.* 75 ppb. The PAS method was proved to be highly sensitive in detecting sub-ppb concentrations of ethylene.[9] Despite their accuracy, these methods are of an industrial scale and lack portable ethylene detection devices for ethylene monitoring and detection. End consumers do not benefit from these, and live monitoring of ethylene in the supply chain and storage is not possible, which does not control deterioration and food loss. Industrial ethylene identification methods involve complex setups and high costs, restricting their use to advanced post-harvest monitoring systems, and real-time storage conditions of climacteric fruits such as bananas, mangoes, and apples are highlighted due to their high ethylene sensitivity, rapid ripening behavior, and significant commercial importance in global trade, making them model commodities for studying ethylene-related post-harvest changes.[10]

Increasing demand for consumer needs and smart packaging research has shifted to portable devices and methods for freshness monitoring and live quality status of fresh produce. Sensors and indicators based on optical and colorimetric activity, which react with ethylene to produce a visible color change, are emerging as cost-effective and easy-to-use alternatives for real-time ethylene detection.[11] These indicators are composed of metal compounds and reactive dyes that react with ethylene produced from the climatic conditions and provide real-time conditions of the produce, which reduces the post-harvest loss and enables end-use consumers to select fresh commodities. Research conducted by Nguyen *et al.* developed a flexible, colorimetric ethylene sensor film using thiol-functionalized polydiacetylene (PCDA-SH) synthesized with Lawesson's reagent. The developed ethylene detection films change their colour from blue to red in the presence of ethylene and measure gas up to 600 ppm in the air, which can be used for kiwi fruit ripening and freshness monitoring.[12] They can be integrated directly into polymer films to provide colorimetric ethylene sensing or, alternatively, used as standalone indicator strips that can be inserted into packaging systems, depending on the application requirements. A novel smart packaging solution provides only qualitative or semi-quantitative measurements rather than precise ethylene concentrations.

This review aims to evaluate the recent advances in smart, portable, and cost-effective packaging technologies for real-time ethylene detection and freshness monitoring in climacteric fruits and vegetables. It discusses about the current sensor materials, their working mechanisms, practical applications, and future prospects in reducing postharvest losses and enhancing supply chain management.

2. Role of ethylene in the growth and deterioration of fresh produce

Ethylene (C_2H_4) is a gaseous phytohormone that is small in size and regulates the growth and development of fruits and vegetables.[4] The influence of ethylene begins from the early lifecycle of plants by controlling the physiological processes of plants, including seed germination, flower development, fruit set, vascular development, and tissue expansion. Ethylene biosynthesis occurs *via* the generation of methionine through the well-developed hormone pathway, in which *S*-adenosylmethionine (SAM) is converted into 1-aminocyclopropane-1-carboxylic acid (ACC) by ACC synthase (ACS) and subsequently to ethylene by ACC oxidase (ACO), as shown in (Fig. 1A and B). In the early stages of plant growth, ethylene is emitted at levels ranging from 0.01 to 0.1 $\mu L\ kg^{-1}\ h^{-1}$, which helps in the development of the plant gene network and single transduction cascade.[13] At low concentrations ethylene acts as a stimulator or inhibitor in the tissue during the development stage and functions in coordination with other hormones including auxins, gibberellins, cytokinins, and brassinosteroids.[14]

As the fruits mature, it is considered as a pre-climacteric stage and ethylene emission increases beyond the pre-climacteric range of 0.2 to 0.5 $\mu L\ kg^{-1}\ h^{-1}$. This increased ethylene release promotes the preparatory signal, which enhances tissue sensitivity to ripening cues and promotes the biosynthesis of antioxidants, carotenoids, phenols, phytochemicals, and cell wall-modifying enzymes.[15] Climacteric fruits such as bananas, mangoes, and avocados continue to synthesize, respond to and metabolize ethylene throughout development, which is sufficient to reach the mature stage. During the ripening phases and harvesting, ethylene production sharply increases to an uncontrolled level of 0.5 $\mu L\ kg^{-1}\ h^{-1}$ to 5 to 100 $\mu L\ kg^{-1}\ h^{-1}$ in climacteric fruits and vegetables; their mechanism is depicted in Fig. 1C, and the ethylene emission level is presented in Table 1. This higher amount of ethylene emission leads to an increase in respiration rate and enhances the ripening chain reaction of biological transformation in fresh produce.[16,17] At the molecular level, ethylene binding to its receptors, namely ethylene response 1 and ethylene response sensor 1, halts the repressive activity of constitutive triple response 1 kinase. This derepression allows the C-terminal

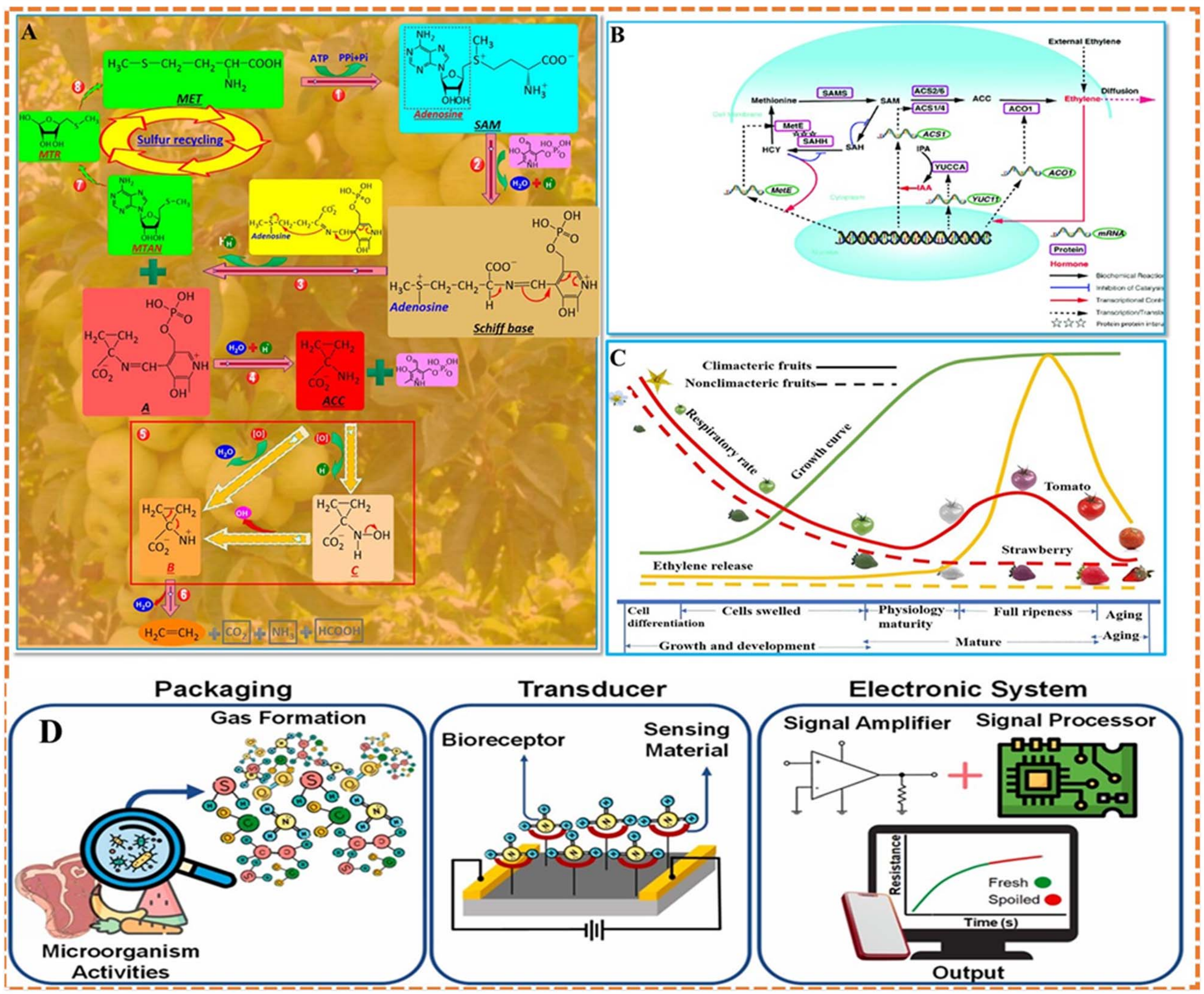


Fig. 1 Systemic representation of ethylene biosynthesis and mechanism for the growth and development of fruits and vegetables, (A) reproduced from ref. 22 with permission from the American Chemical Society,[22] Copyright 2017. (B) Ethylene ripening pathway biochemical network, reproduced from ref. 23 with permission from Horticulture Research,[23] Copyright 2017 2020. (C) Ethylene production in fruits and vegetables during the premature aging stage, reproduced from ref. 24 with permission from Elsevier,[24] Copyright 2021 (D) Gas sensing mechanism for the detection of food quality, reproduced from ref. 25 with permission from Elsevier,[25] Copyright 2024.

fragment of ethylene-insensitive 2 to enter the nucleus, where it activates ripening inhibitor factor.[18] These factors initiate the transcription of downstream genes, ripening inhibitor, non-ripening, and fruit ripening 1, which coordinate to major ripening processes including pigment synthesis, softening, aroma production, and senescence.[19] Ethylene plays a central

Table 1 Ethylene emission levels, ripening time, and storage conditions of various climacteric fruits and vegetables

Produce	Ethylene emission rate ($\mu L\ kg^{-1}\ h^{-1}$)	Ripening time (days)	Storage condition	References
Banana	10–100	4–7	13 °C, 90%	26
Mango	10–70	5–9	12 °C, 85–90%	27
Kiwi	2–30	7–14	0–1 °C, 90–95%	28
Avocado	10–60	5–8	5–6 °C, 85–90%	29
Apple	0.1–10	6–10	0–4 °C, 90–95%	29
Peach	20–120	3–6	0–2 °C, 90–95%	30
Broccoli	1–4	4–7	0–1 °C, 95–100%	31
Tomato	1–10	4–8	13–21 °C, 90–95%	32
Pear	1–20	5–10	0–1 °C, 90–95%	32
Plum	1–10	3–7	0–2 °C, 90–95%	33

role in the degradation of chlorophyll and the accumulation of carotenoids such as lycopene and β-carotene, leading to the characteristic color changes observed in ripened fruits. This process is regulated by ethylene-inducible enzymes such as phytoene synthase (PSY1) and carotenoid isomerase (CRTISO).[20]

Softening of fruits due to ripening results from the ethylene-induced activation of cell wall-degrading enzymes such as polygalacturonases (PG), pectin methyl esterases (PME), and expansins, which disrupt the structural integrity of pectin and cellulose in the fruit cell walls. Over-softening due to excessive cell wall disassembly makes the fruit more vulnerable to physical damage and microbial infection.[13] Senescence processes are also modulated by ethylene. It promotes the generation of reactive oxygen species (ROS), accelerates membrane degradation, and suppresses antioxidant defenses, ultimately shortening the shelf life. Even exposure to trace amounts in the storage or transport environment can trigger premature ripening and senescence, often reducing the commercial value.[21]

3. Classification of ethylene detection technologies

The presence of excess ethylene and oxygen gas leads to the fruit's spoilage, and the absence of oxygen gas leads to the growth of anaerobic microorganisms. Therefore, the monitoring of gases during the ripening process is very crucial to maintain the quality of fruits and vegetables, as presented in Fig. 1D. Intelligent packaging systems get attached to the food packaging material in the form of labels or sensors to monitor the food product quality by providing precise information.[34] Sensors and equipment consisting of a receptor and a transmitter detect or determine changes in the surrounding environment by transferring signals to measure the chemical and physical parameters.[35] Gas sensors and indicators for fruits and vegetables are essential components of smart packaging systems designed to monitor the freshness and quality of produce during storage and transportation, as depicted in Table 2.[36] These sensors detect gases such as ethylene, oxygen, carbon dioxide, ammonia, and hydrogen sulfide, which are either naturally emitted by the produce or generated during ripening and spoilage. The mechanism of gas sensors is based on the quantitative evaluation of volatile compounds inside the food package for quality analysis. The gas sensors interact with the volatile compounds present in the food package, producing a real-time response signal, thus monitoring the food packaging system. By monitoring the changing concentrations and compositions of these gaseous emissions, we gain valuable insights into the physiological state of the fruits and vegetables. This real-time, non-destructive assessment allows for proactive interventions to optimize the storage conditions and prevent premature decay, ultimately contributing to a reduction in food.[37] There are various types of gas sensors, such as sensors that are dipped in food, directly in contact with the food, or sensors that are attached to the packaging system[25,34]

The distinction between "hot" and "cold" gas sensors offers different advantages for preservation applications. Hot sensors, operating at elevated temperatures, exhibit enhanced robustness and resistance to the humid environments often encountered in the storage of produce. Their stability over time ensures reliable long-term monitoring.[38] Conversely, cold sensors, while potentially simpler in design, might be more susceptible to moisture interference. The widespread commercial availability of conductive polymer and metal oxide sensors, in both hot and cold configurations, underscores their favorable balance of sensitivity and cost-effectiveness for detecting the diverse array of VOCs emitted by fruits and vegetables.[39] Besides simply tracking ripening, gas sensors can detect the presence of spoilage-related gases such as ammonia and hydrogen sulfide, which indicate microbial activity. This early detection capability is crucial for identifying spoilage before it becomes visually apparent, allowing for the timely removal of affected produce and preventing further contamination.[40] Furthermore, these sensors can be employed to monitor the atmospheric composition within controlled storage environments, ensuring optimal levels of oxygen, carbon dioxide, and ethylene to extend the shelf life. The ability to create sensor arrays, or electronic noses, using combinations of sensors with varying sensitivities enables the generation of unique "odor fingerprints" for complex gas mixtures, providing a comprehensive assessment of produce quality and freshness throughout the supply chain.[41]

Research conducted by Won *et al.* developed an oxygen sensor using a silver-deposited oriented polypropylene film (cathode), an adhesive gel electrolyte, and a zinc sheet. The sensor detected oxygen concentrations from 0% to 21% with high linearity ($R^2 = 0.999$) and sensitivity (18 mV/% O_2). The studied oxygen sensors show potential for oxidation-sensitive intelligent food packaging.[42] In another study conducted by Das *et al.*, ZnO nanocrystals were synthesized with zinc acetate and sodium hydroxide by spin coating over a glass substrate, and an ethylene sensor was developed. The sensing performance of the ethylene sensor was analysed under natural ambient conditions (~70% RH, 27–28 °C) for guava. The sensor showed a low detection limit of 10 ppm, with a high sensitivity of 27% at 10 ppm and 92% at 200 ppm ethylene.[43]

4. Traditional packaging limitations

4.1 Gas chromatography

Gas chromatography (GC) is one of the most widely used analytical detection and quantification methods for different gases on industrial and laboratory scales, as presented in Fig. 3. GC analysis, an advanced technology, has the ability to analyze and separate various volatile and non-volatile compounds in a single experiment, and has a high level of sensitivity and accuracy in the experiment.[53] Starting from the 1950s, this method has undergone continuous development of instrument sensitivity and accuracy, enabling real-time gas monitoring. GC works on the principle of dividing between the stationary phase, the liquid column, and the mobile phase, inert gases.[54] As a sample is injected into the column, it vaporizes and is carried by the gas column, which interacts with the stationary phase according to its chemical and physical properties. This component of GC separates both phases as the existing time is

Table 2 Smart packaging material response factor, application, and visual response for climacteric fruits and vegetables packaging

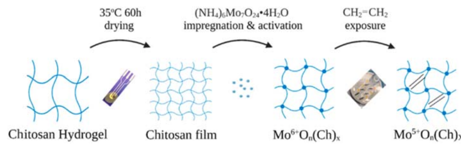
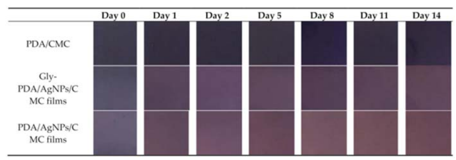
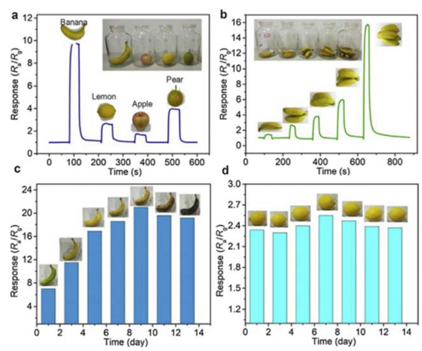
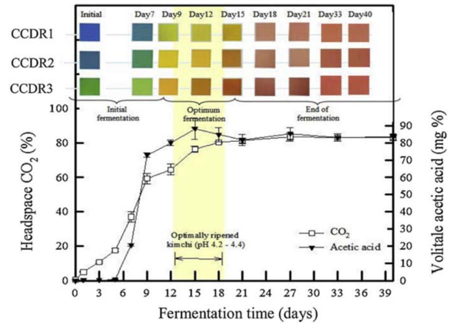
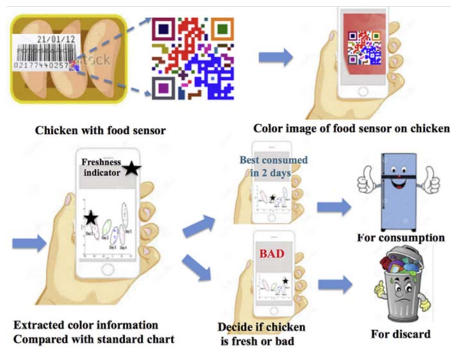
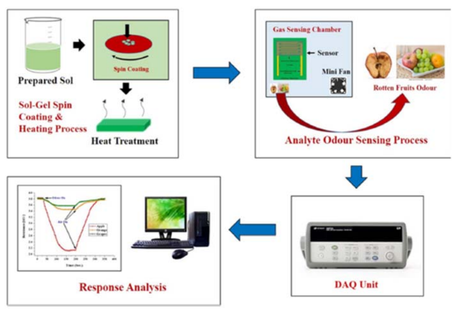
Smart material	Material used	Response	Packaging application	Visual response	Reference
Film	Soy protein isolate, grape-skin red, ZnO nanoparticles	pH	Apple		Reproduced with permission from Elsevier[44]
Electrochemical device	Chitosan–PVA hydrogel, molybdenum	Ethylene	Chip for ethylene sensing in storage		Reproduced with permission from Elsevier[45]
Films	Soy protein isolate, bromothymol blue, and methyl red	Ethylene	Fresh-cut apples		Reproduced with permission from Wiley Online Library[46]
Film	Polydiacetylene, silver NPs, carboxymethyl cellulose	Temperature & time	Quality monitoring of fresh produce		Reproduced with permission from MDPI[47]
Sensor film	Palladium-doped tin(IV) oxide	Ethylene	Ripeness banana		Reproduced with permission from Elsevier[48]
Indicator	Methyl red, bromothymol blue	Freshness, oxygen	Green bell pepper		Reproduced with permission from Elsevier[44]

Table 2 (*Contd.*)

Smart material	Material used	Response	Packaging application	Visual response	Reference
Indicator label	Methyl red (MR), bromothymol blue (BTB), poly(ether-*block*-amide)	pH	Kimchi		Reproduced with permission from Elsevier[49]
Barcode-integrated label	Barcode, freshness sensor	Time–temperature and freshness	Kale ripeness and traceability		Reproduced with permission from Elsevier[50]
Spectroscopic sensor	Pulsed quantum cascade laser	Ethylene	Apple packaging		Reproduced with permission from Nature[51]
RFID-integrated label	RFID, optical/thermal/pressure sensors	Location, temperature, and ethylene traceability	Fruits and vegetables		Reproduced with permission from Wiley Online Library[52]

known as retention time, while the detector (flame ionization detectors (FIDs), thermal conductivity detectors (TCDs), or chemiresistive sensors) records the signal, which detects the concentration of gas or compounds.[55]

With recent innovation and technology development, micro-machined GC columns have enabled efficient separation and identification of low-molecular-weight (≥60 g mol^{-1}) gases, such as ethylene, which has a molecular weight of 28 g mol^{-1}, at low concentration levels of ppb.[10] Modern GC analysis uses preconcentration techniques where an adsorbent carbon molecular sieve is used to trap ethylene due to a high surface area adsorbent tube that is heated up to 200–300 °C while purging inert gas and thermally desorbed into a smaller volume directly into a narrow bore cold trap of GC column and ethylene is separated from residual interferant on the column and detected by the FID/PID.[56] A study conducted by Zaidi *et al.* used micro-GC equipment integrated with a 3D printed column, a SnO_2 sensor, and a micromachine preconcentrator. Ripening banana ethylene concentration was detected, where peak signals were analyzed by fitting a polynomial to correct for baseline drift, yielding a resolution of 12 ppbv. The system effectively detected ethylene emitted from ripening bananas at 306 ppbv, showing the potential of GC for monitoring ethylene and fresh produce ripening during storage and transportation.[57] The figure shows the experimental steps for gas chromatography, and the detector was based on Carboxen 1000 and SnO_2 for ethylene detection. The developed GC setup shown in Fig. 2A has a high sensitivity of ethylene measurement and detects up to 1 ppmv–2 nano liters of ethylene.[58]

4.2 Non-dispersive infrared (NDIR) spectroscopy

Nondispersive infrared (NDIR) technology is a common detection method for certain types of gases, based on the absorption of different gas molecules at specific wavelengths. This system is also known as "fingerprint" because of the unique absorption rate of each gas. In NDIR, the infrared radiation is permitted to interact with gas molecules within a gas cell or chamber, and the difference in transmitted infrared radiation is measured to determine the analyte concentration. Random elements that might affect detection precision in NDIR gas detection systems include ambient influences, detector noise, zero drift of circuit devices, light source instability, and optical path instability. Furthermore, the signal is readily lost in the noise due to the gas's absorption of infrared light, which is just a few thousandths of its initial light intensity. This limits the gas detection limit and makes detection more difficult. Research by De Biasio *et al.* used this system for the detection of ethylene in fruits and vegetables. The study stated that the ethylene concentration was detected to be 20 μm.[59] Fig. 2B shows the 3D structure of the NDIR detector studied by Sklorz *et al.*, using thermopile detectors with specific optical filters, and signal processing was conducted for ethylene detection. The studied system achieved a detection limit of 34 ppmv using digital signal processing and was further improved to 25 ppmv with a lock-in amplifier.[60]

4.3 Flame ionization detector

Flame ionization detector is an analytical instrument that works on the principle of burning carbon compounds, which produces ions for the detection of organic compounds. In flame ionization detection (FID), organic compounds are burned in a hydrogen–air flame, producing ions. The resulting ionic current, which is directly proportional to the concentration of carbon in the sample, is then measured. FID works on the mechanism of combustion, ionisation, and detection. The effluent in the GC mixes with hydrogen and oxygen, which leads to the production of the flame. Further, ionisation occurs where the organic molecules get fragmented into charged ions and

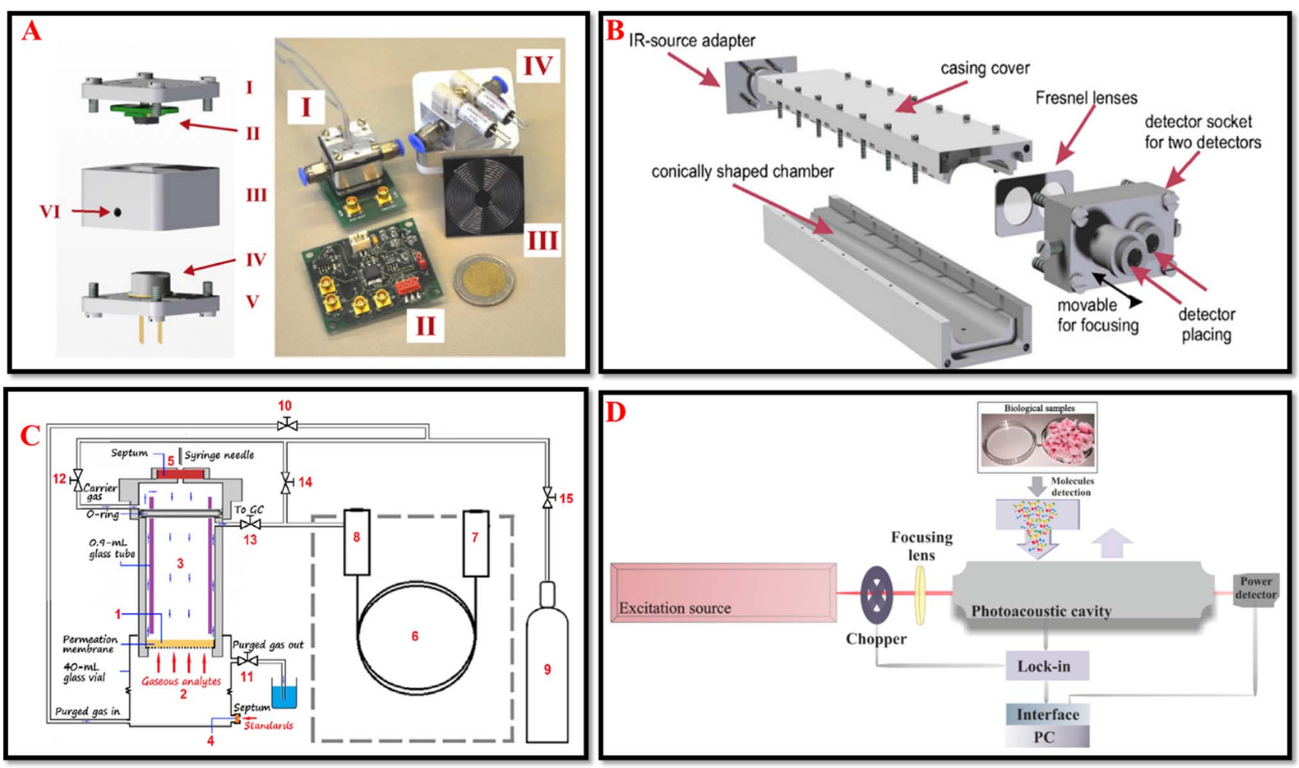


Fig. 2 Schematic representation of the analytical ethylene detection method: (A) GC-MS, reproduced from ref. 60 with permission from Elsevier,[60] Copyright 2012. (B) Non-dispersive infrared technology, reproduced from ref. 66 with permission from Wiley Online Library,[66] Copyright 2025. (C) Flame ionization, reproduced from ref. 60 with permission from Elsevier,[60] Copyright 2012. (D) Photoacoustic spectroscopy, reproduced from ref. 67 with permission from MDPI,[67] Copyright 2019.

electrons during combustion, which analyzes the concentration of the analyte.[61]

This method is based on an empirical method that is independent of the nature of ions collected and the reaction process during flame production. FID is advantageous as it is highly sensitive to the organic compounds, due to which the detection limit is 10^{-12} to 10^{-13} g s^{-1}. FID offers a broad linear response of 6–7 magnitude, which provides accurate quantification. This technique is highly reliable and simple to use; however, there are a few disadvantages in this technique, such as it does not detect inorganic substances, lacks specificity, and requires air for the flame.[62] Nhan *et al.* worked on the detection of methane and ethylene by the flame ionization method using a polymeric material in their research, and the pictorial representation of an equivalent working system is depicted in Fig. 2C. The result showed that the flame ionization for ethylene was 11 times better than the N_2 atmosphere, *e.g.*, the sensitivity of the measurements is also better.[58,61]

4.4 Photoacoustic spectroscopy (PAS)

Photoacoustic spectroscopy (PAS) works on the absorption of the electromagnetic radiation of the analyte molecules by the pressure fluctuations in the form of waves and pulses, as shown in Fig. 3. A sample's molecules are excited and moved to higher electronic or vibrational states when it is exposed to modulated or pulsed light. The extra energy is dissipated as heat when these excited molecules return to their ground state. The sample (or the surrounding medium, like a gas) expands and contracts as a result of the localised heating, creating sound waves or pressure variations.[63] Sensitive microphones, piezoelectric transducers, or other acoustic sensors positioned within or close to the sample chamber pick up these pressure waves. A photoacoustic spectrum, which is directly related to the sample absorption spectrum, is produced by measuring the amplitude of the acoustic signal as a function of the incident light wavelength. This method of gas detection requires no sample preparation, is insensitive to light scattering, and is versatile to solid, liquid, and gas samples. However, there are certain disadvantages such as requiring absorption, possible sample heating, and detector bandwidth for solids.[64] A study conducted used the modulated infrared light source and a non-resonant photoacoustic cell for the detection of ethylene in the mixed gas to be measured.[65] As per the study conducted by Popa *et al.*, photoacoustic spectroscopy using a CO_2 laser was developed to detect ethylene from the cherry, apple, and strawberry flowers, as shown in Fig. 2d, which measured ethylene at 75–78 ppb with high sensitivity for ethylene gas detection.[9]

5. Smart packaging for ethylene detection: overview and mechanism

Smart packaging devices and ethylene detection technology can be used to monitor the quality of ethylene-sensitive and climatic commodities. The visual and digital quality monitoring of commodities can help detect fruit ripening and deterioration, reduce waste, and help the supply chain. Optical sensors,

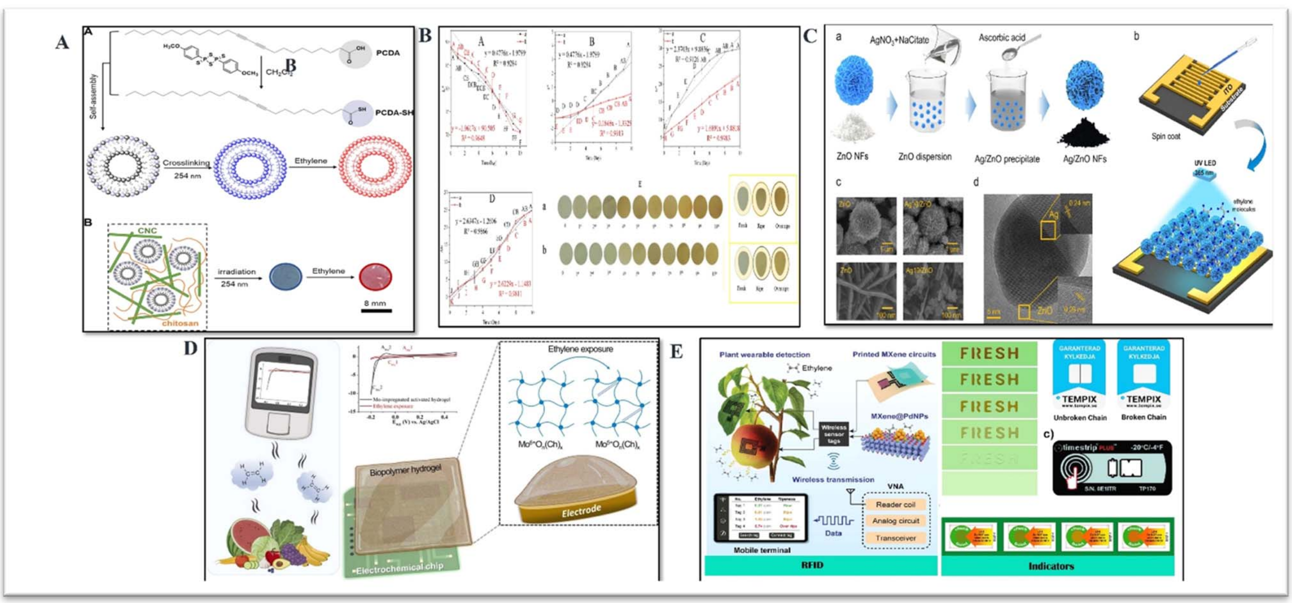


Fig. 3 Systematic representation of smart packaging material: (A) PCDA, LR reagent-based ethylene indicator film, reproduced from ref. 12 with permission from the American Chemical Society,[12] Copyright 2020. (B) Dual-mode CuNP/N@CQD indicator, reproduced from ref. 75 with permission from Elsevier,[75] Copyright 2025. (C) Ag-decorated ZnO sensor, reproduced from ref. 78 with permission from the American Chemical Society,[78] Copyright 2024. (D) Chitosan PVA-based electrochemical chip, reproduced from ref. 45 with permission from Elsevier,[45] Copyright 2023. (E) Working of ethylene RFID and indicator, reproduced from ref. 91 with permission from Wiley Online Library,[91] Copyright 2023.

colorimetric sensors, color-changing indicators, and RFID are recent technologies for ethylene monitoring.

5.1 Indicators

The food packaging indicators are packaging materials that show the presence and absence of specific substances and the quality of the product in the packaging headspace by showing a visual colour change, as shown in Fig. 3E. The most used indicators in smart packaging for fresh produce packaging are pH indicators, time temperature indicators, humidity indicators, gas indicators, freshness indicators, ethylene indicators, *etc.*[68] These indicators are composed of color-changing dyes and pigments that react with changes in their environment and provide a real-time condition of the product.[69] When they react with a particular condition, they change color because of a light absorption shift. An indicator printed with the reference colour helps consumers have a better experience in selecting the product.[70] Indicators generally function *via* chemical interactions such as tautomerism, redox reactions, or acid–base interactions. The visible color change occurs as a result of the chemical interaction between the indicator compound and ethylene gas, which alters the molecular structure and optical properties of the sensing material. The current available indicators for fruits and vegetables is a freshness indicator that detects spoilage, degradation, sensory changes, and texture loss in fresh produce due to chemical changes that release volatile compounds, including ammonia and hydrogen sulfide.[71]

Gas indicators are the indicators that are used for identifying critical gases that are responsible for the growth and spoilage of the product. Fruits and vegetables typically deteriorate due to ethylene production and a higher respiration rate.[72] Excessive ethylene release accelerates the spoilage; thus, the ethylene indicator will help to control early ripening during storage and transportation for future global food loss reduction. Fresh produce, including raw and ready-to-eat, cut fresh produce, becomes an important segment that will benefit from the industry in terms of consumer interaction and food waste reduction.[73]

A colorimetric filter paper-based indicator was prepared by Shin *et al.*, using a potassium permanganate solution. The developed indicator changes its colour from purple to brown upon exposure to ethylene (1000 $\mu L\ L^{-1}$), and kiwi fruit ripening was analyzed.[74] In a study conducted by Lohrasbi Nejad *et al.*, a filter paper-based dual-mode colorimetric ethylene indicator was developed *via* the incorporation of nitrogen-doped carbon quantum dots and copper nanoparticles (CuNPs/N@CQDs) into an agar hydrogel. The developed indicator changes its colour from pale green to yellow and brown and detects ethylene up to 9.94 μM. Ethylene interacts with copper nanoparticles in the indicator, causing nanoparticle aggregation and a red shift in plasmon resonance, leading to a visible color change, as shown in Fig. 3B.[75] The figure shows silica (SiO_2) nanoparticles (Fig. 4A) fabricated over the paper surface with palladium sulfate and ammonium molybdate to develop a flexible ethylene indicator that changes its colour from white to blue in the presence of 50–150 ppm of ethylene.[76] The ripening indicator was developed to measure the degree of colour ripening in apple fruits for 30 days. Metal ion-doped indicators change their colour from white/yellow to blue as per the ethylene emission and degree of ripening.[77] An ethylene sensor was prepared, as shown in Fig. 3C, using silver nanoparticles and zinc oxide (ZnO) nanoflowers, spin-coated over the indium-doped tin oxide electrodes. Ethylene sensing response at room temperature was 52.83% at 40 ppm. Silver-decorated ZnO sensors can be used for banana ripening and ethylene monitoring.[78]

Ethylene indicators and labels offer real-time fresh produce freshness and ethylene monitoring technology. The advancement of bio-sourced materials and nanotechnology will improve the sensitivity, sustainability, and consumer acceptability, which will ensure the smooth functioning of the global supply chain of fresh produce.

5.2 Sensors

The novel packaging technology development of sensors emerges as a transformative shift to enhance food safety and quality monitoring of food products. Sensor-based smart fruit and vegetable packaging integrates developed chemical or biological sensors into a packaging material to monitor, detect, and communicate packaged produce quality and conditions.[79] These smart packaging devices, *i.e.* sensors embedded in packaging materials, detect gases such as oxygen, carbon dioxide, ethylene, ammonia, and nitrogen, which are used as key indicators of food freshness for quality monitoring. Food packaging sensors used technologies such as optical sensors, colorimetric sensors, electromechanical sensors, and biosensors.[10] Sensors are composed of electronic devices with the help of transducers that detect and convert one form of signal into another, as presented in Fig. 4. Based on their sensor working mechanism, they are classified as active and passive sensors. Active sensors generate signals without any external stimulation, and passive sensors respond to changes in humidity, pH, and colour to control and monitor the produce during storage and transportation.[80] Ethylene sensors can be broadly classified into three categories based on their working principles. Physical sensors (*e.g.*, resistance- or capacitance-based devices) detect changes in electrical properties caused by ethylene adsorption on sensor surfaces.[81] Chemical sensors (*e.g.*, colorimetric films and electrochemical probes) rely on specific reactions between ethylene and sensing materials, resulting in measurable color or current changes.[82] Biosensors, in contrast, employ biological recognition elements such as enzymes, antibodies, or DNA aptamers to achieve high specificity toward ethylene.[82] This classification helps distinguish the mechanisms and applications of different sensing platforms used in smart packaging.

These sensors use pH-sensitive dyes and an enzyme substrate reaction to generate an electrical signal to analyse the condition. Sensor-based ethylene-detecting devices are becoming an emerging tool for smart packaging and monitoring the ripening stage of fresh produce.[37] Chemiresistive sensors use the material copper(I) complexes combined with single-walled carbon nanotubes, which bind the repelling ethylene molecules over the sensor surface, developing an

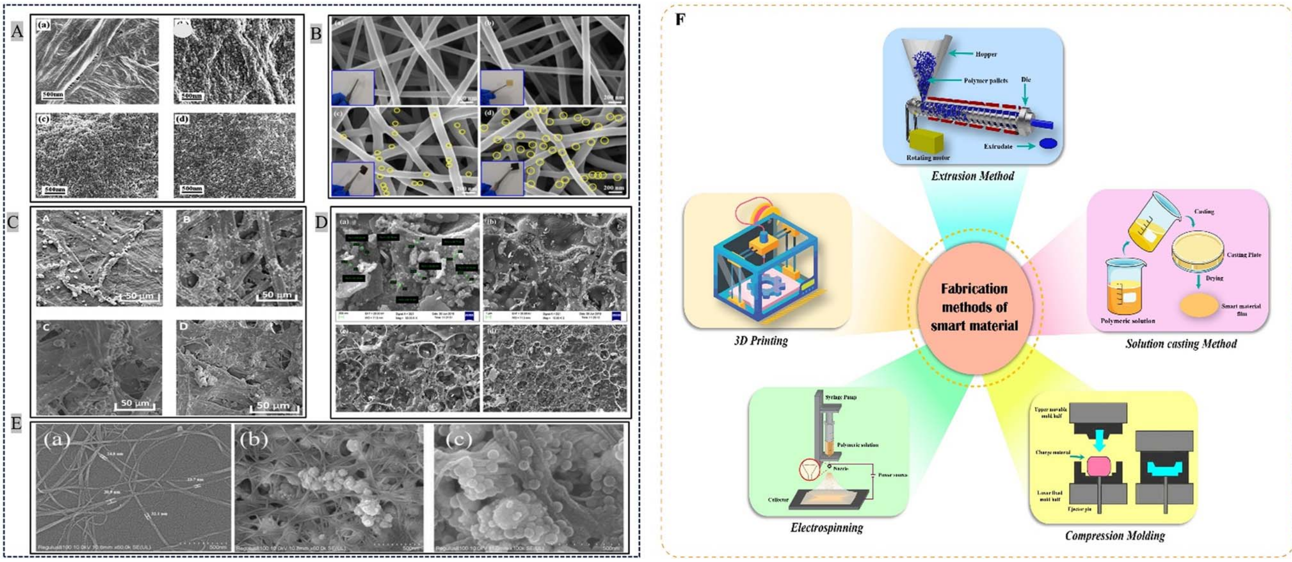


Fig. 4 Fabrication and manufacturing techniques for the development of smart packaging materials for live ethylene monitoring, adapted from (A) Surface of the prepared PDDA/SiO_2 indicator reproduced from ref. 76 with permission from IOP Science,[76] Copyright 2006. (B) ZIF-8/PAN nanofibers, reproduced from ref. 99 with permission from Elsevier,[99] Copyright 2024. (C) Silicon dioxide nanoparticles, reproduced from ref. 84 with permission from Elsevier,[84] Copyright 2017. (D) Si-SnO_2 film surface morphology reproduced from ref. 95 with permission from Springer,[95] Copyright 2019. (E) PdNP-SWCNT nanocomposite surface reproduced from ref. 86 with permission from Elsevier,[86] Copyright 2023. (F) Smart material fabrication and development method.

electrical resistance in the flow channel and providing ethylene concentration in the packaging headspace. A colorimetric sensor is a visual indicator that changes its color in the presence of ethylene.[83] A paper-based plasma-assisted cataluminescence sensor was developed by doping nanoparticles over the paper surface, and the system detects ethylene (33–6667 ppm). The coating of silicon dioxide nanoparticles can be observed in Fig. 4C, which can be used as catalysts.[84] A study conducted by Li *et al.* used the colorimetric sensory array method for live monitoring of ethylene using the low-cost dyes printed on a porous membrane. The developed sensor can detect ethylene below 0.25 ppm, showing its high sensitivity and accuracy, where the colour of the sensor changes from light yellow to brown due to a palladium-based dye that undergoes a reduction reaction, showing visible ethylene concentration, and is used for banana ethylene monitoring.[85]

Another study conducted by Yan *et al.* developed a paper-based ethylene sensor using single-walled nanotubes, palladium nanoparticles, and polystyrene microspheres by laser writing, and the PdNP-SWCNT nanocomposite network structure can be seen in Fig. 4E, which provides an active surface area. The developed sensor detected ethylene concentrations as low as 100 ppb at room temperature for ripening monitoring. It showed high sensitivity, excellent flexibility, and durability over 1200-fold cycles. Real-time tests with bananas confirmed its ability to track fruit ripeness and spoilage over 12 days.[86] Zinc oxide/carbon nanofibers were synthesized by electrospinning of zeolitic imidazolate framework-8/polyacrylonitrile (ZIF-8/PAN) solutions to develop a nanosensor. The resulting three-dimensional (3D) porous network structure, shown in Fig. 4B, with a high specific surface area and embedded ZnO (zinc oxide) nanoparticles, enables the detection of ethylene at 100 ppm.[87] Sensors integrated into smart packaging are rapidly gaining interest in food science, materials science, and electronics, providing sustainable and consumer-friendly solutions to ensure food safety and reduce waste. An emerging trend in smart packaging is the integration of wireless and IoT-enabled sensors, which can transmit ethylene concentration data in real time to cloud-based systems. Such platforms create a digital record of a product's storage and transport history, enhancing supply chain transparency and enabling predictive shelf-life management. By coupling low-cost ethylene sensors with RFID, Bluetooth, or NFC modules, packaging can function not only as a passive container but as an active data node within the food distribution network.

5.3 Radio frequency identification (RFID)

Radio Frequency Identification-based food packaging has emerged as a transformative wireless technology that provides accessibility to real-time monitoring, tracking, and quality maintenance of products throughout the supply chain.[52] RFID tags consist of readers and antennas. Readers control communication with RFID tags using a control unit and radio frequency interface; they can receive and transmit data *via* one or more antennas. RFID antennas enable data transmission about the product between the reader and tags by converting electrical energy into radio waves.[88] These RFID tags are integrated with sensors to monitor temperature, humidity, gas composition (*e.g.*, CO_2 and NH_3), pH, and package integrity, providing real-time data to reduce food waste and ensure food safety. Active RFID systems contain an internal power source, enabling longer reading ranges and continuous signal transmission, but at a higher cost. In contrast, passive RFID tags are powered by the reader signal, making them less expensive and suitable for disposable food packaging, though with a shorter reading range.

RFID tags integrated with gas sensors help in the detection and monitoring of ethylene and manage the ripening of fruits and vegetables in a packaging environment, as shown in Fig. 3E. This RFID system is typically employed with the metal oxide semiconductor and electrochemical sensing element integrated with an RFID transponder. Metal oxide-based RFID function of the principle of conductivity changes when exposed to ethylene gas molecules adsorbed over the RFID surface, creating a resistance that results in the detection of ethylene concentration.[89] Electrochemical RFID sensors work on the redox reaction at the electrode surface, where the oxidation of ethylene occurs and produces a single current, which is equal to the ethylene gas concentration present in the packaging headspace. These sensors are attached with the RFID chip that converts analog sensor readings into digital signals, which allow the RFID tag to wirelessly transmit the ethylene level.[90]

An RFID-based electrochemical chip was developed, as shown in Fig. 3D, using the chitosan–PVA hydrogel infused with molybdate ions and coated onto a microfabricated gold electrode system for ethylene monitoring. The ethylene exposure induces a redox reaction where Mo^{6+} is reduced back to Mo^{5} and generates an electrical signal, which is detected by the electrochemical chip and shows the presence of ethylene up to 100–200 ppm.[45] In an experiment conducted by Li *et al.*, an RFID-based ethylene detection system was developed using the MXene-printed resonators with wireless radio frequency (RF) technology. These printed resonators change their electrical property in the presence of ethylene gas, which is detected using an RFID reader and measures ethylene up to 10 ppm. In this system, ethylene interacts with the MXene material, causing a change in the dielectric property that enables real-time monitoring.[91] Despite their potential, RFID-based systems face challenges such as high implementation costs, limited consumer awareness, and concerns over data security. Future improvements should focus on reducing cost, enhancing compatibility with biodegradable packaging, and integrating with IoT platforms for real-time monitoring.

6. Design and manufacturing technology

The advancement in food manufacturing and packaging technology for fruits and vegetables has shifted to modern-day technology and devices, including smart sensors and RFID, to ensure the transparency, freshness, and higher shelf life of the product, as depicted in Fig. 5. Ethylene freshness indicators are designed and developed using natural dyes or chromogenic compounds by the coating and printing technology, which changes its colour in the presence of ethylene.[92] The developed sensors for ethylene detection composed of nanomaterials, zeolitic imidazolate frameworks, curcumin composites, or anthocyanins are embedded in biodegradable matrices such as chitosan, starch, or cellulose acetate to produce responsive indicators that visually or electronically reflect ethylene presence.[83]

Immobilization methods such as physical adsorption, covalent interaction, or ionic bonding are employed to fix the dyes or sensors into the matrix. The RFID technology has enhanced smart packaging by enabling the wireless non-contact transmission of product information. These devices can be linked with ethylene detectors, transmitting information about the gas concentration, humidity, and temperature throughout the product supply chain.[93] Various manufacturing techniques are being used, as shown in Fig. 4F, to fabricate this packaging system, including compression moulding, solvent casting, 3D printing, electrospinning, extrusion, and non-contact printing. Thermo-compression molding and electrospinning have also been employed to create responsive films and nanofiber-based indicators with high sensitivity to ethylene and other spoilage-related volatiles.[94] Ethylene sensor films were developed by the spin coating method, and the surface structure of nickel-doped tin(IV) oxide (Ni-SnO_2) sensor films, shown in Fig. 4D, was used to develop ethylene sensors having 80% sensitivity for ethylene monitoring.[95]

The advanced method of 2D and 3D printing allows for multilayered, customized packaging materials with precise functionality. The integration and application of smart manufacturing revolutionize packaging systems by incorporating AI, IoT, and automation into material processing, device fabrication, and packaging lines according to the Industry 4.0 paradigms.[96] Smart manufacturing and packaging strategies allow the scalable production of sensor-based films, accurate coating, and digital quality control during the packaging. These packaging strategies and manufacturing methods integrate functional materials and innovative fabrication for the development of smart packaging materials and packaging technology for fruit and vegetable packaging and ethylene monitoring, which reduces food spoilage, ensures food safety, and maintains the freshness of produce.[97] As per the study conducted by Deng *et al.*, a humidity sensor has been developed by a spin coating method using an FR4 substrate with etched I-type slots for encoding ID information and sensing humidity. The sensing unit consists of three identical slots coated with silicon nanowires (SiNWs) deposited *via* spin-coating. The developed sensor shows potential for humidity monitoring.[98]

7. Applications of ethylene-based indicators in different food products

7.1 Banana

Banana is the most commonly consumed fruit by customers; therefore, it is important to acknowledge ethylene production at every stage, from harvesting to storage. Banana is a climacteric fruit that undergoes respiration and produces ethylene gas during the ripening process. The production of ethylene in bananas has significant effects on the quality, such as color changes, softening, flavor, and aroma. The excess production of bananas leads to the spoilage of bananas and over-

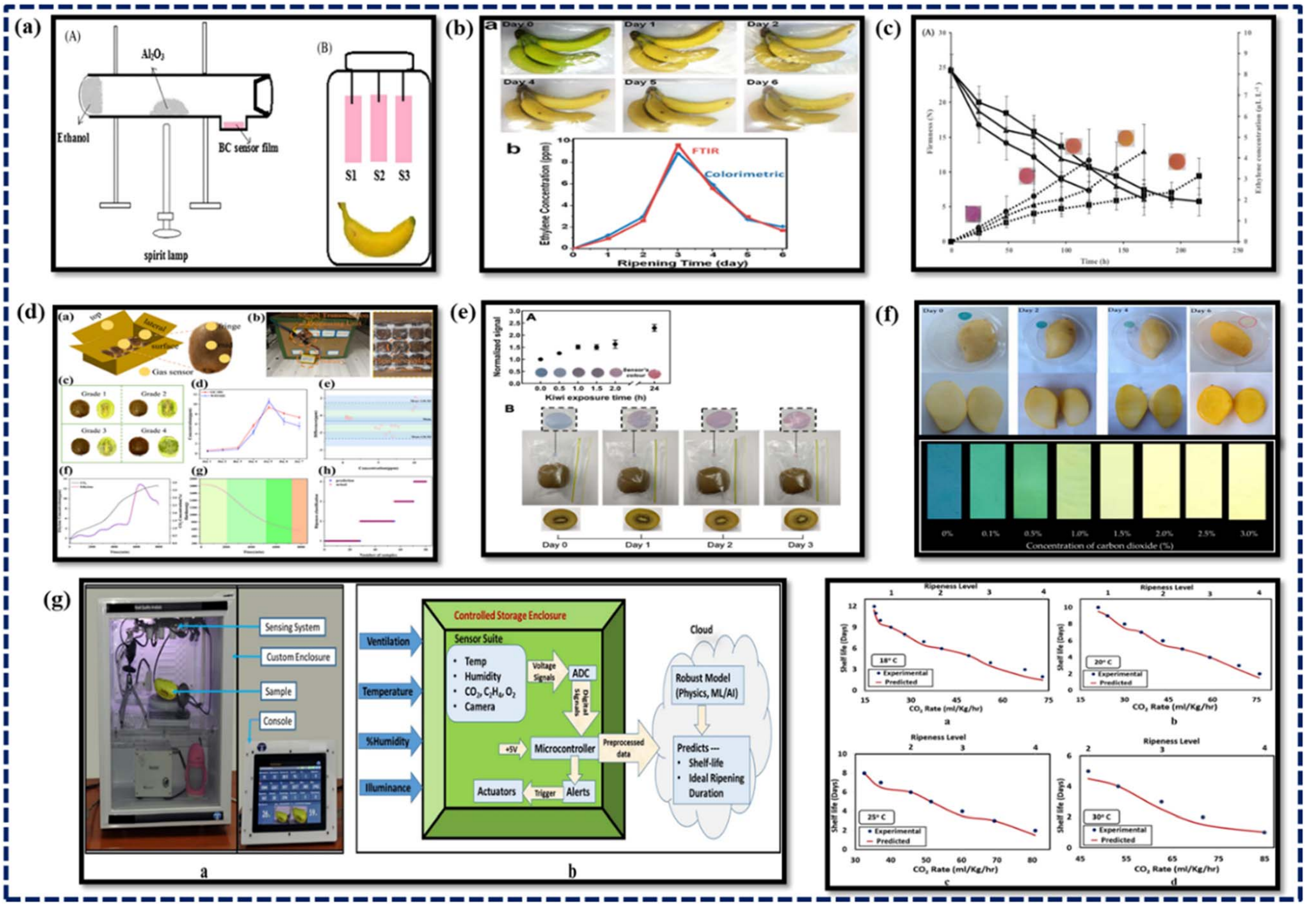


Fig. 5 (a) Schematic representation of the ethylene gas detection sensor film, reproduced from ref. 109 with permission from Wiley Online Library,[109] Copyright 2018. (b) Ethylene monitoring by the MKS model 2030 FT-IR multigas analyzer, reproduced from ref. 85 with permission from the American Chemical Society,[85] Copyright 2019. (c) Schematic representation of ethylene gas concentration and change in firmness during the kiwifruit ripening process for different packaging films under different temperature conditions, reproduced from ref. 74 with permission from Elsevier,[74] Copyright 2023. (d) Placement of ethylene gas sensor and *in situ* monitoring of kiwi for 7 days, reproduced from ref. 110 with permission from the American Chemical Society,[110] Copyright 2024. (e) Ethylene detection in the headspace of kiwi packaged in a PCDA/PCDA-SH sensor film and color transition of the sensor with ripe kiwi over time, where the sensor response is normalized to 1 kg of ripe kiwi, reproduced from ref. 111 with permission from Elsevier,[111] Copyright 2021. (f) Change in the color of ethylene and carbon dioxide-based indicators with the change in the ripeness of packaged mango fruit at 27 °C, where blue represents unripe, light green color represents half ripe, and yellow color represents full ripe, reproduced from ref. 112 with permission from MDPI,[112] Copyright 2021. (g) Schematic representation of the IoT and cloud sensing system, temperature-controlled enclosure, and shelf-life study of Kesar mangoes, reproduced from ref. 113 with permission from Springer,[113] Copyright 2023.

ripening.[100,101] Therefore, it becomes essential to maintain the ethylene concentration and ripening state of the banana. The preservation of bananas is done by minimizing the concentration of ethylene during harvesting, transportation, packaging, and storage.[102]

The traditional methods preserved bananas by wrapping them in plastic or banana stems to slow down the ripening and browning. With advancements in technology, active food packaging has helped in the preservation of bananas. The introduction of ethylene absorbers into the packaging helps in the delay of ripening. In current scenarios, researchers are trying to develop sensors and indicators for the determination of ethylene concentration, which prevents spoilage, as shown in Fig. 4. A study by Pirsa and team developed an optical sensor using a portable bacterial cellulose (BC) nanofiber film doped with $KMnO_4$ for ethylene detection and the preservation of bananas. From the results, it was observed that the storage time and temperature affected the concentration of ethylene gas in bananas, as shown in Fig. 5(a).[103] Another research study by Li *et al.* developed a calorimetric sensor array for the detection of ethylene gas. From the study, it was observed that as the concentration of ethylene increases, there is a color change from green to yellow, as depicted in Fig. 5(b).[85]

7.2 Kiwi

Kiwi is a climacteric fruit that is matured after the harvesting process for several months at a low temperature. The storage performance mainly depends on the maturation of kiwi at the time of harvest, which overall affects the quality of kiwi fruit, influencing consumer acceptability.[85] Kiwi fruit is impacted by oxidation and ethylene emission, which leads to the spoilage and growth of pathogenic fungi, such as *Botryosphaeria* sp., *Phomopsis* sp., and *Botrytis cinerea*. Kiwi fruit is highly sensitive to ethylene emission, which regulates the softening and ripening. At low concentrations of ethylene, the maturation of kiwi is significantly accelerated, which leads to an increase in softening rate, respiration rate, and production of volatile aroma and flavor. Therefore, there should be proper regulation and monitoring of ethylene release. In earlier days, kiwi was stored on wooden beds or tray boxes to prevent damage during transportation. Further transition to modern packaging developed plastic trays and ventilated corrugated boxes. Recent advances in packaging have developed various ethylene-based packaging films and indicators for monitoring ethylene gas, as presented in Fig. 5. A research study by Shin and team has developed an indicator EVOH film based on $KMnO_4$, and a change in the color of the film was observed at temperatures of 15 °C, 20 °C, and 25 °C in kiwifruit packaging for 30 h. The ethylene concentration, kiwifruit firmness, and indicator color were observed. When the kiwifruit ripeness reached 7.9 N the ethylene concentration was different, and the color changes were observed, as shown in Fig. 5(c). The results showed that the accumulation of ethylene gas changed the color of the film from purple to brown, which influenced the kiwifruit ripening for 6 days.[74]

A recent study has developed a flexible wearable chemoreceptive ethylene gas detector using Pd/TiC_2T_x-based nanocomposites for controlling kiwifruit ripeness. The ethylene sensors were placed in a box containing kiwifruit, the signal was transmitted and fabricated using laser direct writing methods which collects and converts the ethylene gas into the ethylene concentration and produces a generated data *via* an antenna as shown in Fig. 5(d) From the results, it was analyzed that the fabricated sensor could monitor the ethylene release, which improved in preventing the kiwi fruit.[104] A similar work study by Nguyen *et al.* developed a polydiacetylene-based sensor for ethylene detection *via* a color change, as shown in Fig. 5(e). The sensor color changes from blue to red due to the reaction between polydiacetylene and Lawesson's reagent. The limit of the ethylene detection was 600 ppm, which was easy to use.[12]

7.3 Mango

Mango is a climacteric fruit that is most consumed in summer because of its unique flavor and aroma. During the ripening stage, the organic matter is oxidized, which results in the production of large amounts of energy, carbon dioxide, and water.[105] The release of ethylene regulates the physiological and metabolic properties of mango during the ripening process. The production of ethylene helps in the development of aroma, flavor, sugar production, and color change in mangoes. However, when there is an excess of ethylene production, the mangoes get spoiled easily, leading to softening and off-flavor.[106] Certain biobased coatings are applied to preserve mangoes and delay the ripening process. Researchers have also developed a few sensors to determine the shelf life of mangoes.

A recent study by Noiwan and team has developed a methylcellulose-based indicator film for the monitoring of the ripeness of mangoes. In this study, a pH-based indicator dye, methylene red and bromothymol blue, was prepared for the determination of the freshness of mangoes. The changes in the carbon dioxide concentration change the pH during storage, formed during respiration, as shown in Fig. 5(f).[107] Research by Dutta *et al.* has developed an AI-based sensor for the shelf life of Kesar mangoes. In the study, the AI model was trained on the basis of collected data and images of mangoes, as shown in Fig. 5(g).[108] Another research study by Li *et al.* developed an ethylene gas sensor based on a PtO_2 detector and SnO_2 for monitoring fresh mangoes at room temperature. From the results, it was found that there is a correlation between the spoilage date and the maximum ethylene released.[85]

8. Challenges and future directions

Smart food packaging refers to the overall protection of food products from deteriorating before reaching the consumer. The advancement and development of smart food packaging offer significant opportunities to enhance the shelf life, safety, and quality monitoring of fresh produce.[114] However, several challenges need to be addressed or modified to achieve the maximum potential of this advanced technology. Smart packaging materials for fresh produce sensors, indicators, and RFIDs and their integration into the packaging headspace without affecting the functionality ensure the sensitivity and high specificity in the detection of spoilage due to ethylene, maintaining smart device stability throughout the product shelf life and reducing the cost for large-scale production, along with addressing environmental and health issues.

Traditional smart packaging materials used for the live monitoring of fruits and vegetables are unsuitable for various fresh produce, where packaging must conform to irregular shapes, while maintaining the breathability of produce. Low-level ethylene (below 0.1–1 ppm) detection by these devices becomes a major challenge to overcome without being affected by the other volatile compounds released from fresh produce.[4] Emerging ethylene indicators and sensors show potential, but there is a lack of potential for commercial use. The integration of these materials into thin, flexible films, which maintains the sensitivity while withstanding mechanical stress during transportation and storage, shows a technical hurdle.

The real-time monitoring of fresh produce conditions, temperature, humidity, and gas composition is another major challenge. Most smart packaging solutions rely on single-point data measurement rather than continuous monitoring throughout the supply chain. Printed electronics and wireless sensors embedded in packaging can provide live produce condition durability under high cold storage or high moisture conditions, which must be improved. High-precision ethylene sensors and IoT-enabled tracking systems are currently expensive, limiting their use to premium produce. To address this, researchers are exploring low-cost alternatives such as colorimetric ethylene indicators (*e.g.*, dye-based films that change color upon ethylene exposure) and paper-based sensors. These solutions could provide affordable, visual spoilage alerts for consumers while integrating with smartphone apps for quantitative analysis. Governments and retailers could also incentivize adoption through subsidies or dynamic pricing models that reward reduced food waste.

Future innovation for ethylene monitoring and smart packaging of fruits and vegetables can be combined with CO_2/O_2 detectors to provide a comprehensive view of produce freshness. For instance, a spike in ethylene combined with rising CO_2 levels could trigger automated alerts for immediate quality intervention in the supply chain. Research with industry and academia can improve the functionality and reduce the cost of development of a multifunctionality indicator. The integration of self-regulation, IoT, and blockchain technology further enhances the traceability of ethylene data of produce from farm to retail. Advances in nanomaterials, wireless sensing, and circular design will optimize the next generation of fruit and vegetable packaging that not only monitors ethylene, but also extends the shelf life of produce. Future developments in ethylene-responsive smart packaging will likely focus on integrating highly sensitive, low-cost sensors with biodegradable packaging materials. Advances in nanotechnology, colorimetric dyes, and digital monitoring systems are expected to make real-time ethylene detection more reliable and accessible, ultimately enabling better shelf-life management and reducing post-harvest losses.

9. Conclusion

The monitoring and detection of ethylene become crucial for maintaining the freshness of fresh produce and protecting it from deterioration. Ethylene detection and live monitoring technology were reviewed in this paper. The review highlights the promising approach to smart packaging for preserving fresh produce and reducing loss due to over-ripening and higher ethylene emission. The role of ethylene for the growth and ripening of climatic fruits and vegetables during the early, premature, and harvesting stage. Gas sensors and indicators that leverage chemical reactions to signal the presence of ethylene, along with smart packaging strategies that embed these indicators or sophisticated sensors directly into packaging materials, represent significant advancements. An advanced method and smart packaging for ethylene gas detection, gas chromatography, shows potential for lab and industrial-scale ethylene monitoring.

Indicators, sensors, and RFIDs are emerging technologies that offer excellent results for live ethylene monitoring and maintaining the freshness of fresh produce, enhancing end consumer interaction with the product through a colour-changing appearance and wireless detection. Indicators and sensors used for ethylene detection differ in their functions. Indicators are passive systems that give visual or semi-quantitative information through colour changes, while sensors are active devices that provide precise quantitative signals and provide information about the product. Advanced manufacturing techniques for developing ethylene detection materials have been studied, including 3D printing, electrospinning, and thermo-compression molding, enabling scalable, customizable, and high-precision sensor-based packaging. Various studies have been conducted to evaluate the smart material's potential for freshness monitoring, with applications on mango, banana, and kiwi, demonstrating its capability for real-time fresh produce packaging and preservation. The ethylene monitoring materials and devices reviewed in this paper present immense potential in enhancing freshness, safety, and shelf life; however, several challenges must be addressed to achieve their full impact. Future research on ethylene-responsive smart packaging should focus on developing cost-effective, biodegradable materials, such as starch-based polymers, cellulose nanofibers, or protein-based films, which can incorporate sensing and active components without increasing the production costs. The integration of blockchain and IoT platforms could enable the real-time monitoring of ethylene levels and automatic data sharing across the supply chain, ensuring transparency from producers to retailers. Additionally, policymakers and industry stakeholders play a crucial role in establishing regulatory standards, incentivizing the adoption of sustainable packaging and supporting the pilot-scale commercialization of these initiatives. Ultimately, advancing these areas will not only enhance the practical viability of smart packaging but also contribute to reducing global food waste, improving supply chain transparency, and promoting sustainability in postharvest management.

Author contributions

Pradeep Kumar contributed to investigation, visualization, data curation, and writing—original draft. Shefali Tripathi contributed to figure preparation, manuscript editing, review, and formatting. Ram Kumar Deshmukh contributed to manuscript editing, reviewing, and formatting. Bhushan P. Meshram contributed to figure preparation and formatting. Lavanya contributed to figure preparation and formatting. Kirtiraj K. Gaikwad contributed to conceptualization, data curation methodology, resources, writing, review and editing, visualization, project administration, validation supervision, and funding acquisition.

Conflicts of interest

The authors declare that there are no conflicts of interest.

Data availability

The data and materials are available from the corresponding author.

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