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Original Paper

Apple Damage Detection Using Ethylene Gas Sensors

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Abstract

To improve the automation and accuracy of postharvest apple quality grading and damage detection, and to overcome the inherent limitations of conventional manual inspection methods—most notably strong subjectivity, low operational efficiency, and the lack of support for online monitoring—this study develops an intelligent apple damage detection platform based on ethylene gas sensors. On this basis, a damage level identification approach is proposed that exploits the dynamic characteristics of ethylene concentration. Apples of the same harvest season (Red Fuji) were selected as experimental samples and subjected to three treatments: undamaged, mildly damaged, and severely damaged. Ethylene concentration dynamics were continuously monitored over a five-day period under controlled temperature and humidity conditions. The results indicate that both the absolute levels and growth rates of ethylene concentration differ significantly across damage categories. Moreover, the average relative growth rate of ethylene concentration increases monotonically with the severity of damage.

Using the ethylene concentration growth rate as a key feature, a support vector machine (SVM) classification model was constructed to identify apple damage levels, and its performance was systematically compared with that of a recognition method based on image shape features. The experimental results demonstrate that, when ethylene growth rate features are employed, the SVM model achieves consistently high classification accuracy across multiple kernel functions. Among these, the radial basis function kernel exhibits the best performance, with an average recognition accuracy exceeding 97%, substantially outperforming approaches that rely solely on image-based features.

Overall, the findings provide strong evidence that apple internal damage can be identified with high precision by leveraging the dynamic behavior of ethylene concentration. This study thus offers a feasible and accurate solution for online postharvest apple quality monitoring and grading, and provides a valuable reference for nondestructive internal damage detection in agricultural products.

Keywords

Apple damage identification, Ethylene concentration, Gas sensors, Support vector machine, Nondestructive detection

1. Introduction

As the world's largest producer of apples, China accounted for approximately 57.3% of global apple output in 2024, thereby occupying a dominant position in the international apple industry. In stark contrast to this scale advantage, however, China's apple exports remain predominantly concentrated in low- and mid-end markets, with high-end market penetration accounting for less than 10%. This pronounced disparity reflects a set of structural challenges confronting the Chinese apple industry in its transition toward higher value-added production, among which the relative underdevelopment of postharvest handling technologies constitutes a primary constraint. Specifically, substantial gaps persist between domestic practices and international advanced standards in critical processing stages such as cleaning, waxing, grading, and packaging. As a consequence, the majority of apples produced in China are marketed immediately after harvest, whereas access to high-end markets typically necessitates standardized and technologically intensive postharvest processing. Improving the accuracy and sophistication of apple quality grading is therefore indispensable to altering the current export structure and enhancing overall market competitiveness (Zhao & Wu, 2014).

In recent years, intelligent apple detection technologies centered on gas sensors have demonstrated notable advantages in the field of nondestructive fruit quality assessment. Such technologies effectively address the inherent limitations of conventional manual visual inspection methods, which are often characterized by strong subjectivity, labor-intensive procedures, and susceptibility to sample destruction. By contrast, gas sensor–based detection offers a rapid, objective, and highly sensitive means of evaluating fruit quality, rendering it particularly suitable for online monitoring during apple storage and transportation. Through continuous acquisition of physiological signals, these technologies enable real-time quality surveillance and provide a technological foundation for automated postharvest management. Nevertheless, while gas sensing techniques targeting volatile organic compounds (VOCs), ethanol, and ethylene have achieved relatively high levels of commercialization and practical deployment, many other sensor-based approaches for apple quality evaluation remain largely confined to laboratory settings. Their broader application and industrialization continue to depend on further theoretical refinement and systematic validation in real-world environments. A growing body of empirical research has explored the feasibility of gas sensing technologies for apple quality and damage detection (Yang & Wen, 2020).

Li Ying et al. (2015) employed a PEN3 electronic nose to monitor key quality indicators, including firmness, soluble solids content, and titratable acidity, and achieved a prediction accuracy of 92.0% for apple storage duration using a multilayer perceptron neural network. Zou Xiaobo et al. (2005) developed a self-constructed electronic nose system based on a metal oxide semiconductor sensor array combined with a genetic algorithm–optimized radial basis function neural network, demonstrating that principal component analysis effectively discriminated between sound and defective apples, while the optimized neural network achieved a classification accuracy of 96.4% on the test set. Yin et al. (2023) designed a monitoring prototype integrating a gas sensor array with temperature and humidity sensors and applied a simulated annealing–partial least squares (SA-PLS) model to predict apple decay time, obtaining a correlation coefficient of 0.936 and an RMSEP of 0.828. Ma et al. (2023) developed a low-cost electrochemical sensor system with an ethylene detection limit as low as 0.413 ppm and a response time under 50 s, making it suitable for real-time monitoring of apple ripening. Yumoto et al. (2021) employed infrared laser absorption spectroscopy to achieve real-time measurement of ethylene dynamics in 'Red Fuji' apples, attaining a sensitivity of 0.8 ppb and a temporal resolution of 1 s.

Collectively, these domestic and international studies indicate that a relatively comprehensive technical framework has emerged, encompassing sensor hardware development, multi-factor modeling, and algorithmic optimization. Substantial progress has been achieved in areas such as real-time monitoring capability, early warning potential, and system portability. Despite these advances, further integration of sensing technologies with robust analytical models remains essential for translating laboratory-scale successes into scalable postharvest applications.

Against this backdrop, the present study aims to develop an intelligent apple damage detection platform based on gas sensor technology. Ethylene gas sensors are employed to quantify the ethylene concentrations released by undamaged, mildly damaged, and severely damaged apples, and the corresponding ethylene concentration growth rates are analyzed to elucidate their relationship with damage severity. On this basis, a support vector machine–based predictive model is constructed to identify apple damage levels, thereby providing an effective methodological framework for nondestructive postharvest damage assessment.

2. Materials and Methods

2.1 Experimental Methods

Apples of the same harvest season (*Red Fuji*) with comparable size and mass were selected as experimental materials and divided into three groups according to damage condition: undamaged, mildly damaged, and severely damaged. A square area measuring 20 mm × 20 mm was marked on the surface of each apple as the observation region. Prior to treatment, the marked area was gently cleaned with alcohol-soaked cotton to remove surface contaminants and ensure consistent surface conditions. To simulate mechanical impacts commonly encountered during harvesting and transportation, apples were subjected to free-fall impacts onto a rigid floor. Drop heights of 20 cm and 40 cm were applied to represent mild and severe damage conditions, respectively.

Before the formal experiment, all apples were equilibrated at 25 °C and subsequently held at room temperature for 24 h in order to minimize postharvest heterogeneity and reduce potential interference with subsequent measurements. To investigate the effects of damage severity on ethylene release behavior, a total of 300 apples of the same cultivar were selected and evenly assigned to three treatment groups—undamaged, mildly damaged, and severely damaged—with 100 samples per group. Each apple was individually sealed in a gas-tight bag and stored at a constant temperature of 25 °C in a laboratory environment with controlled humidity, thereby ensuring uniform external conditions across treatments.

Ethylene concentration within the sealed bags was measured at predetermined sampling intervals using an ethylene gas sensor. For each group, mean ethylene concentrations at each time point were calculated and used to construct ethylene release profiles, allowing characterization of the temporal dynamics of ethylene emission. During each measurement, a small sampling port was created in the sealed bag, through which the sensor probe was briefly inserted and immediately resealed. The system was then allowed to stabilize for approximately one hour before the ethylene concentration reading was recorded. To enhance measurement reliability, zero calibration was performed prior to each sampling by exposing the sensor to ambient air and confirming a zero output response. This procedure ensured the accuracy and consistency of subsequent measurements.

The experiment was conducted continuously over a five-day period, during which ethylene concentration data for all treatment groups were systematically recorded to capture the temporal evolution of ethylene release associated with different damage levels.

2.2 Experimental Equipment

To ensure stable monitoring and reliable recording of ethylene concentration during fruit quality assessment, an online detection platform was developed comprising an ethylene gas sensing probe, a gas detection transmitter, and integrated power supply and display/data acquisition modules (as illustrated in Figure1). At the sensing stage, a modular ethylene probe was employed to continuously monitor the ethylene concentration in the vicinity of the apple samples in real time. The probe was specifically designed for ethylene detection, with a measurement range of 0–100 ppm, and provided a standard 4–20 mA current loop output, thereby facilitating robust signal transmission and seamless system integration. The online gas detection transmitter operated with a DC power supply of 24 ± 12 V and featured an IP66 protection rating, enabling reliable performance under conditions commonly encountered in fruit inspection environments, including dust and elevated humidity. The transmitter supported both 4–20 mA and RS485 output interfaces. In consideration of system compatibility and implementation simplicity, the 4–20 mA current loop was selected for data transmission in this study. The transmitter consumed less than 2.5 W of power and was designed to operate within an ambient temperature range of -20 to 60°C, thereby meeting the stability requirements of both laboratory experiments and potential field applications. The entire platform was powered by a unified 24 V DC supply. To mitigate electromagnetic interference during signal transmission, shielded cables were used to connect the sensing probe and the transmitter. The transmitter output was subsequently routed to the display and data acquisition unit, enabling real-time visualization and continuous recording of ethylene concentration. All measurements were conducted in a relatively stable indoor environment. The sensor probe was positioned in close proximity to the samples while avoiding direct contact, and standard preheating and stabilization procedures were performed prior to data acquisition. These measures effectively minimized the influence of residual gases, airflow disturbances, and fluctuations in temperature and humidity, thereby enhancing the repeatability and reliability of the collected data.

Figure 1. Standard Ethylene Gas Concentration Detector

2.3 Identification Algorithm

Support Vector Machine (SVM) is a supervised learning framework that formulates pattern recognition problems as quadratic optimization tasks by jointly employing the principle of structural risk minimization and kernel-based transformation techniques (Shigehiko Hayashi, Katsunobu Ganno, Yukitsugu Ishii, et al., 2002). Depending on the separability of the data, SVM-based classification problems can be broadly categorized into two classes: linearly separable and nonlinearly separable cases (Van Henten, Van Tuijl, & Hemming, 2003).

For linearly separable binary classification problems, the central objective of SVM is to identify an optimal separating hyperplane that discriminates between two classes while maximizing the margin between them. By maximizing this inter-class separation, the classifier achieves enhanced generalization performance and robustness to perturbations in the input data. The resulting hyperplane is uniquely determined by a subset of training samples, referred to as support vectors, which lie closest to the decision boundary and play a decisive role in defining the classifier.

In contrast, when the data are not linearly separable in the original feature space, SVM employs kernel functions to implicitly project the input features into a higher-dimensional space in which linear separability can be attained. Within this transformed feature space, a linear SVM is then applied to perform classification. This kernel-based strategy enables SVM to effectively capture complex nonlinear relationships without explicitly computing the high-dimensional mapping, thereby preserving computational efficiency while substantially extending the model's representational capacity.

3. Results and Analysis

Figure 2 illustrates the ethylene concentration trajectories of 300 apple samples monitored over the experimental period.

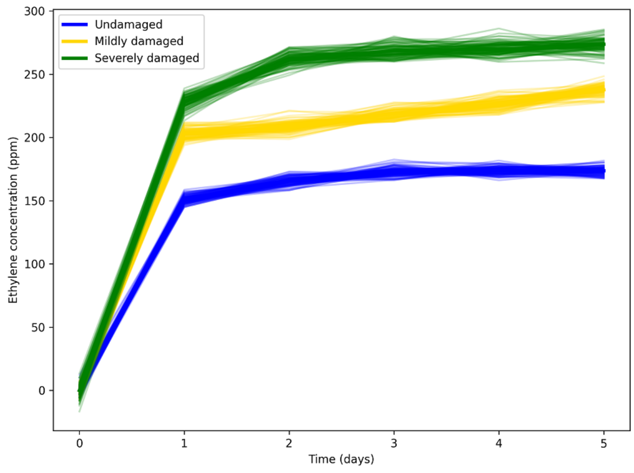

Figure 2. Changes in Ethylene Gas Concentration

Figure 2 presents the temporal variation in ethylene concentration of apples with different damage severities over a five-day period. Undamaged apples exhibit the lowest ethylene concentrations throughout the observation window, accompanied by a slow and stable growth pattern. This outcome is attributable to the fact that these apples remain in a state of natural ripening, characterized by stable cellular metabolism, whereby ethylene release is driven primarily by normal physiological processes and thus maintained at a relatively low level.

Apples subjected to mild damage display intermediate ethylene concentrations, following a steady upward trajectory over time. Because mild damage affects mainly surface tissues, the associated cellular stress response remains limited in intensity, resulting in a comparatively moderate ethylene release rate. Moreover, as the damaged regions gradually undergo partial recovery during later stages of storage, the rate of ethylene accumulation correspondingly decelerates, leading to a more tempered growth profile.

In contrast, severely damaged apples consistently exhibit the highest ethylene concentrations and the most rapid rate of increase. A free-fall impact from a height of 40 cm induces extensive tissue rupture, widespread cell death, and accelerated microbial proliferation. These processes substantially enhance the activity of ethylene biosynthesis enzymes, thereby triggering a pronounced escalation in ethylene production. Consequently, ethylene emissions from severely damaged apples remain markedly higher than those observed in the undamaged and mildly damaged groups.

To mitigate the influence of within-group individual variability on the overall trends, daily ethylene concentration measurements from the 100 replicate samples in each group were first averaged, yielding mean ethylene concentration time series for each damage category, As shown in Table 1.

Table 1. Average Value of Ethylene Concentration Time Series

Damage condition	Day 1	Day 2	Day 3	Day 4	Day 5
Undamaged	151.1	165.6	173.1	174.1	173.7
Mildly damaged	203.1	208.6	219.1	226.7	237.7
Severely damaged	228.1	261.3	268.7	269.6	273.7

To further quantify the temporal dynamics of ethylene emission across damage categories, the average relative growth rate (RGR) of ethylene concentration was calculated for each group according to the following expression:

$$RGR_i = \frac{C_{i,5} - C_{i,1}}{C_{i,1}} \times 100\%$$

where RGR_i denotes the average relative growth rate of ethylene concentration for the i-th damage group, $C_{i,5}$ represents the mean ethylene concentration of the i-th group on Day 5, and $C_{i,1}$ corresponds to the mean ethylene concentration of the i-th group on Day 1.

Applying the relative growth rate formulation yields average ethylene concentration growth rates of 14.9%, 17.1%, and 20.1% for the undamaged, mildly damaged, and severely damaged groups, respectively. The monotonic increase in the average relative growth rate with escalating damage severity indicates that greater mechanical damage is systematically associated with accelerated ethylene accumulation. This pattern suggests that increasing damage severity not only precipitates a rapid decline in fruit tissue vitality but also markedly activates ethylene biosynthesis pathways, thereby intensifying metabolic processes linked to senescence and deterioration.

4. Experimental Validation

Accordingly, the ethylene concentration growth rate of 300 apple samples was extracted as the primary feature for model construction, and a support vector machine (SVM) was employed to perform damage level prediction. Of the total samples, 240 were randomly selected to form the training set, while the remaining 60 samples were reserved for model testing.

In the predictive model based on the ethylene growth rate feature, the penalty parameter was set to $C = 1$. For the polynomial kernel, the kernel order was specified as $q = 2$; for the radial basis function (RBF) kernel, the kernel parameter was set to $\sigma^2 = 1$; and for the Sigmoid kernel, the parameters were configured as $\alpha = 1/2$ and $\beta = -1$. The corresponding classification results are summarized in Table 2.

Table 2. Use an Ethylene Concentration Growth Rate Prediction Model

Kernel function	Number of support vectors	Average accuracy (%)	Runtime (ms)
Polynomial	156	94.3	167
Radial basis function (RBF)	189	96.4	118
Sigmoid	205	97.5	243

For comparison, a predictive model based on damage-related image features was constructed under an identical SVM framework. The penalty parameter was fixed at $C = 1$. For the polynomial kernel, the kernel order was set to $q = 3$; for the radial basis function (RBF) kernel, the kernel parameter was specified as $\sigma^2 = 0.5$; and for the Sigmoid kernel, the parameters were configured as $\alpha = 1/3$ and $\beta = -1$.

Table 3. Use the Raw Image Prediction Model

Kernel function	Number of support vectors	Average accuracy (%)	Runtime (ms)
Polynomial	148	73.4	195
Radial basis function (RBF)	176	84.1	178
Sigmoid	186	81.9	215

A comparison of Tables 2 and 3 indicates that when apple damage is identified solely on the basis of raw image features, the highest recognition accuracy achieved—using the radial basis function kernel—is limited to 84.1%. In contrast, when the ethylene concentration growth rate is employed as the feature parameter, all kernel-based predictive models attain average recognition accuracies exceeding 85%, with the radial basis function kernel achieving a peak accuracy of 97.5%.

This pronounced performance disparity provides strong supporting evidence that apple internal damage can be identified both feasibly and with high precision by leveraging ethylene concentration dynamics. The results further suggest that ethylene-based features capture critical physiological information that is not readily observable from surface image characteristics alone.

5. Conclusion

This study proposes an apple damage detection approach based on ethylene gas sensing technology. Using ‘Red Fuji’ apples subjected to different damage severities—namely undamaged, mildly damaged, and severely damaged—as the research object, an online ethylene concentration monitoring platform was established. Under controlled temperature and humidity conditions, continuous measurements were conducted to examine the temporal dynamics of ethylene emission. The experimental results demonstrate that apples with different damage levels exhibit significant differences in both ethylene release intensity and growth patterns. In particular, the average relative growth rate of ethylene concentration increases monotonically with damage severity, reaching 14.9% for undamaged apples, 17.1% for mildly damaged apples, and 20.1% for severely damaged apples. These findings indicate that mechanical damage not only accelerates the decline of tissue vitality but also markedly activates ethylene biosynthesis pathways, thereby expediting quality deterioration.

Building on these observations, the ethylene concentration growth rate was extracted as a feature parameter to construct a support vector machine (SVM) classification model for apple damage level identification. The performance of this model was systematically compared with that of a conventional image-based damage recognition approach. The results reveal that when only image shape features are used, the highest recognition accuracy achieved by the radial basis function kernel is limited to 84.1%. By contrast, when the ethylene concentration growth rate is employed as the input feature, the SVM model with a radial basis function kernel attains a peak recognition accuracy exceeding 97%, representing a substantial improvement in classification performance.

Overall, this study verifies the feasibility and effectiveness of utilizing dynamic ethylene concentration characteristics for rapid and nondestructive identification of internal apple damage. The proposed approach provides a valuable reference for online postharvest apple quality monitoring and grading, and it also offers methodological insights that may be extended to nondestructive internal damage detection in other agricultural products.

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