



Beyond the Naked Eye: Using Thermal Cameras to Detect Hidden Deterioration in Fresh Produce

*Satish Kumar Gaharwariya, Anurag Soni, Fahmidha, Jhalaknath Sharma and Raviprakash Balasundaram

ICAR-Indian Agricultural Research Institute, New Delhi, India

*Corresponding Author's email: gaharwariyaiari@gmail.com

Fresh fruits and vegetables are often valued for their vibrant appearance, texture, flavour and nutritional benefits. Yet beneath the surface, deterioration can begin long before visible spoilage appears. A fruit may look perfectly healthy from the outside while internal bruising, early mold activity or tissue breakdown has already begun. This hidden deterioration contributes significantly to postharvest losses across supply chains. With growing pressure to reduce waste, improve food security and maintain consistent product quality, new inspection technologies are becoming essential. Among these, thermal imaging is emerging as a promising approach capable of detecting spoilage earlier than the human eye or many conventional inspection tools. The idea of using heat signatures to evaluate freshness may sound futuristic, but the principle is grounded in biological and physical reality. Living plant tissues continuously exchange heat with their surroundings through respiration, moisture loss and biochemical activity. When damage occurs, these thermal patterns begin to shift. By capturing subtle temperature differences with infrared cameras, thermal imaging offers a non-destructive method to reveal internal deterioration before it becomes visible. This technology, once reserved for military surveillance or industrial diagnostics, is gaining attention in food science as a tool to safeguard quality from farm to fork.

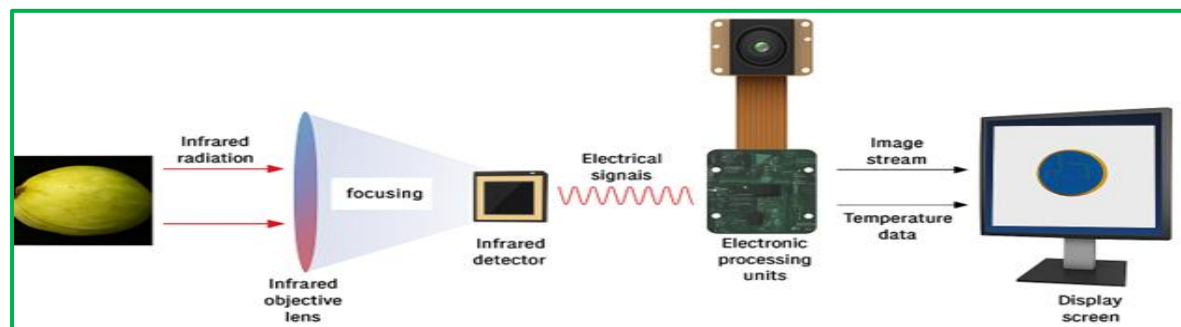
Why Spoilage Goes Unnoticed

The deterioration of fresh produce is a complex biological process influenced by mechanical injury, microbial invasion, enzymatic breakdown and physiological stress. Spoilage often begins at the cellular level, especially when a fruit experiences bruising or environmental shock. Mechanical damage from harvesting, transport or handling can rupture internal cell structures while leaving the outer skin intact. Microorganisms such as fungi exploit these microscopic openings and initiate decay before any visible mold forms. Respiration rate also plays a role. Fruits and vegetables are living biological systems that continue metabolic activity after harvest. As tissues age or become damaged, respiration patterns change, and these metabolic shifts can affect heat distribution. Because the early stages of decay often occur beneath the skin, traditional inspection methods whether visual sorting or manual squeezing struggle to identify deterioration early enough to prevent waste. This lag allows damaged produce to enter supply chains, where decay accelerates, spreads and often leads to large-scale rejections in later processing stages.

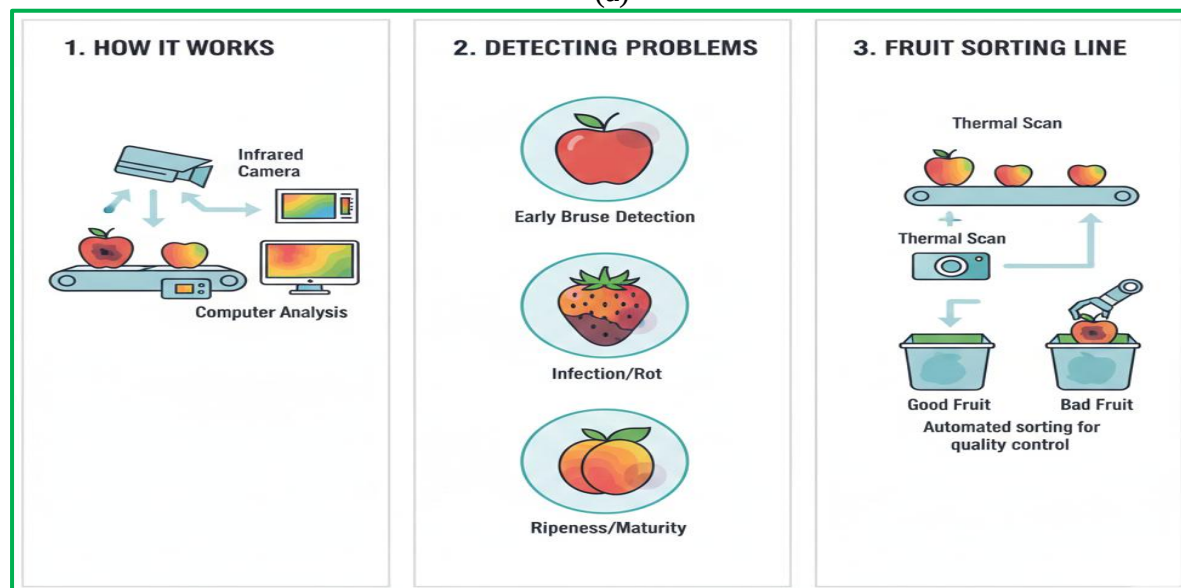
How Thermal Imaging Works

Thermal imaging technology detects infrared radiation emitted naturally from objects based on their temperature Figure 1. All living tissues continuously emit heat, and thermal imaging sensors convert these emissions into thermal maps known as thermograms. Unlike visible-light photography, which depends on reflected light, thermal imaging measures radiated

energy. This means that a fruit can reveal differences in internal condition even if it looks perfectly uniform to the naked eye.



(a)



(b)

Figure 1. (a) Working process of thermal imaging, (b) Overview of thermal imaging for fruit quality.

Modern thermal cameras analyse thousands of temperature points across the surface of an item, creating a high-resolution heat profile. Variations as small as 0.1°C can be detected depending on the system. Fresh, healthy tissue tends to maintain uniform temperature distribution. In contrast, damaged or deteriorating regions may appear warmer or cooler due to changes in respiration, microbial activity, moisture migration or cell breakdown.

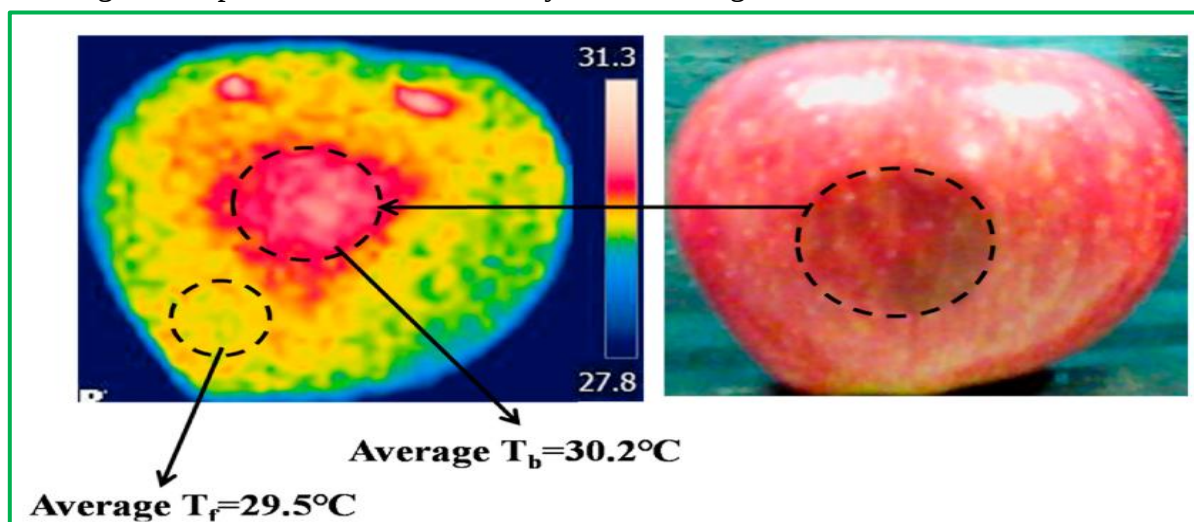


Figure 2. Example thermal image showing hidden bruising in apples (Mahanti et al., 2022).

Why Temperature Differences Reveal Spoilage

Temperature irregularities in produce provide diagnostic insights because they are tied to biological responses. When cells are damaged, they often release water and nutrients that support microbial growth. Bacterial or fungal metabolism produces heat, creating localized warm spots. In other cases, internal bruising may restrict airflow or moisture movement, causing cooler regions. This means thermal signatures can shift in either direction depending on the cause and stage of deterioration. Moisture also plays a role. As produce begins to decay, water distribution changes. Some tissues lose moisture rapidly, while others retain it abnormally, altering evaporative cooling behavior. Since evaporation is a cooling process, regions with compromised cellular integrity sometimes appear cooler than intact areas. These small gradients, though invisible externally, become clearly distinguishable through thermal imaging. In addition, respiration rate increases when fruits undergo stress or decay. Respiration is an exothermic process, meaning it releases heat. This increase creates detectable hot spots. Combined, these biological and physical mechanisms allow thermal imaging to highlight internal spoilage patterns that humans cannot visually detect.

How Thermal Imaging Compares to Other Quality Inspection Technologies

Multiple non-destructive inspection methods are used in the food industry, each with strengths and limitations. Table 1 below illustrates how thermal imaging compares to some widely used approaches.

Table 1. Functional Comparison Between Thermal Imaging and Other Quality Inspection Systems.

Technology	Detects Internal Damage	Requires Sample Contact	Cost Level	Ability to Detect Microbial Activity	Suitability for Industry Automation
Visual Inspection	Low	No	Low	Very Low	High
Near-Infrared (NIR) Spectroscopy	Moderate-High	No	High	Moderate	Moderate
Hyperspectral Imaging	Very High	No	Very High	High	Moderate
X-ray Imaging	High	No	High	Low	High
Thermal Imaging	Moderate-High	No	Moderate	High	High

Thermal imaging occupies a valuable middle position. It is more affordable and easier to integrate into automated sorting systems than hyperspectral or X-ray imaging, yet it reveals far more detail than visual screening. Unlike many technologies that require calibration for each commodity, thermal imaging can be used broadly, although optimized interpretation models improve performance.



Figure 3. Thermal imaging system integrated into a postharvest sorting line.

Uses Across the Food Supply Chain

The value of thermal imaging extends across multiple points in the fresh produce system. During harvesting, it can help detect heat stress or bruises caused by handling injuries shown in Figure 2. Early sorting at packing houses can identify compromised fruit before storage shown in Figure 3, preventing decay from spreading through bulk shipments. During transportation, thermal monitoring can help maintain the integrity of cold chains by

identifying produce lots undergoing abnormal heat production. In storage rooms, thermal technology can detect “hot spots” in stacked packaging where microbial colonies may be forming. Retail applications are also emerging, allowing store operators to monitor freshness and prioritize near-expiry produce for consumer incentives rather than waste. Perhaps most importantly, thermal imaging has the potential to assist farmers and processors in predicting spoilage rather than simply reacting to it. By analyzing thermal patterns over time, predictive models can estimate where deterioration is likely to accelerate. This capability can support smarter inventory rotation strategies, reduce disposal volumes, and increase consumer satisfaction and food safety.

Challenges and Advancements in Technology

Despite its promise, thermal imaging is not without limitations. Environmental factors such as ambient temperature, airflow, lighting conditions and humidity can influence thermal readings. Differences in fruit surface texture or wax coatings may also cause variation. Consistency requires calibration protocols to ensure reliable measurements across lots, seasons and cultivars. Furthermore, interpreting thermal maps requires sophisticated image-processing algorithms and sometimes integration with machine learning to differentiate normal variation from meaningful indicators of spoilage. However, ongoing advancements are rapidly addressing these challenges. Machine-learning-enhanced thermal imaging systems are increasingly capable of distinguishing subtle patterns linked to specific decay mechanisms. Research is also exploring hybrid systems that combine thermal imaging with hyperspectral or NIR data, producing multi-layer visuals where biological signals become easier to interpret. Another promising development involves compact, low-cost thermal sensors integrated into handheld inspection devices and smart sorting equipment.

Future Directions and Potential Impact

As concerns about food waste and sustainability intensify, technologies that help maintain product quality and reduce discard rates will become increasingly valuable. Fresh produce loss accounts for billions of dollars annually worldwide and contributes to unnecessary resource use in land, water and energy. Thermal imaging provides a pathway to earlier detection and better decision-making. With improved artificial intelligence integration, the technology may evolve into predictive analytics tools capable of estimating shelf life or identifying produce at risk before deterioration becomes irreversible. In the future, thermal imaging could also be incorporated into smart packaging that monitors temperature signatures in real time. As sensors become thinner, cheaper and more energy efficient, intelligent packaging systems may alert retailers or consumers before spoilage occurs. This aligns with broader trends toward digitized supply chains and traceability systems that combine IoT technologies with advanced diagnostics.

Conclusion

Thermal imaging bridges an important gap in fresh produce quality assurance: the ability to identify early internal deterioration before it becomes visible. By providing a non-invasive, fast and scalable method of inspection, it offers meaningful benefits for growers, processors, transport operators and retailers. While challenges related to calibration and environmental interference remain, rapid technological improvements and integration with machine learning are making the method increasingly practical. As the food sector continues to pursue waste reduction and improved quality monitoring, thermal imaging is poised to become an essential component of next-generation postharvest management.

Reference

1. Mahanti, N. K., Pandiselvam, R., Kothakota, A., Chakraborty, S. K., Kumar, M., & Cozzolino, D. (2022). Emerging non-destructive imaging techniques for fruit damage detection: Image processing and analysis. *Trends in Food Science & Technology*, 120, 418-438.