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MONITORING THE CONDITION OF VEGETABLES, FRUITS AND PLANTS USING INFRARED THERMOGRAPHY

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Abstract. Determining the quality of fruit and vegetable products and their storage is a topical problem, as evidenced by a significant number of works from near and far abroad. These works present the worldwide experience of using various optical methods for instrumental non-destructive assessment of the maturity and commercial quality of fruit and vegetables. Despite so many scientific works on this topic, the thermographic methods require further research to find out the prospects of using modern thermal imaging systems in the agricultural sector. The paper studies the possibility of using remote-sensing infrared thermography to monitor the state of vegetables, fruit, and plants during their growth and storage. To determine the quality of fruit and vegetable products by random sampling, apples, pears, and pumpkins, with no external (visible) damage, were tested for the presence of microbial infections in them during rotting. In a laboratory environment, the plants were studied after watering to determine the process of hydration through the trunk and leaves and thus assess their condition. The research used a matrix infrared thermograph developed by V.Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine. The studies have shown that infrared thermography detects internal damage to fruit and vegetables and allows assessing the watering of plants and their condition. As a result of this work, it has been shown that infrared thermography, as a diagnostic method, can be recommended for timely detection of the internal development of microbial infections that lead to spoilage of vegetables and fruit during long-term storage, as well as for monitoring the state of plants during their hydration. It has been shown that infrared thermography can be used to control the quality of fruit and vegetable products before putting them in long-term storage and during it. The method allows timely detection of damage, and is helpful in studying plants in the laboratory and in the field.

Keywords: remote-sensing infrared thermography, vegetables, fruit, plants.

Introduction. Formulation of the problem

The innovative development of crop cultivation is aimed at increasing the profitability of production and sales of agricultural products. So, it requires constantly monitoring the quality and ripeness of fruit and vegetables at all stages, from harvesting to the shop counter [1-10]. It is also important to study the state of plants and not to be late with identifying any damage that leads to disruption of the hydration process and affects their development [11-13]. Assessing the ripeness and commercial quality of fruit and vegetables is important for providing people with high-quality products and minimising the costs of storing them. This is a topical issue in many countries of the world.

Analysis of recent research and publications

In the world practice, optical techniques play a key role in non-destructive assessment of ripeness and quality of fruit and vegetables. A detailed analysis of these research methods was performed at I.Michurin All-Russian Research Institute of Horticulture [8,9].

The colorimetric method of diagnostics has been wide introduced. It is shown that the change in colorimetric characteristics is due to aging, changes in the amount of chlorophyll, anthocyans, and other pigments during ripening, storage, heat treatment, and other processes [14,15].

An important physical and mechanical parameter of a fruit is its hardness. It is used to assess the potential storability, the degree of ripeness. It was experimentally checked whether there was any correlation between the hardness of fruit and the degree of spatial coherent reflection of laser radiation from the surface of the object, and certain results were obtained [16].

The amount of chlorophyll is estimated by fluorescence in the apple skin in the blue and red regions of the spectrum. It was shown [17] that fruit with a high chlorophyll content in the skin had higher fluorescence intensity.

When ripening in the garden, fruit have higher fluorescence intensity, while during storage, the intensity decreases to the minimum level [12]. Thus, the fluorescence method can be used to assess the ripeness of fruit and determine how long their shelf life is.

These methods have some disadvantages. The main ones are that they are highly laborious, and that measurements in them involve destroying the object measured. Besides, they are inapplicable for detecting minor surface defects. Optical non-invasive methods based on colour, spectrozonal, or luminescent characteristics of vision systems only register certain modifications of the biochemical composition of tissues. That is why they are ineffective when changes in the commercial quality and ripeness are only accompanied by structural and anatomical rearrangements.

The time of harvesting vegetables and fruit determines their after-harvest quality, too. Complex processes of heat and mass transfer take place between fruit and the environment. In a laboratory environment, using a Varioskan 2011 thermograph, it was found that the temperature difference between the surface of the fruit and the environment with free convection could range from 6°C to tenths of a degree [18].

Remote-sensing infrared thermography (RIT) is used in a variety of industries. Thermography is effective in medicine and veterinary science [19-21]. Quite a number of works are devoted to the thermographic study of trees in order to determine how much they are damaged by pests or how old they are. This is of particular importance for preservation of relict and rare species. Thermography is a reliable modern method of scientific research. It is used as a diagnostic technique in plant breeding [13-18], in assessing the development of harmful microflora after mechanical damage to fruit [18], to register thermal effects in plants that underwent cold stress [5], for climate control in rooms where vegetables are stored [22], and in studies of changes in plant genotypes [29].

In recent years, there have been reports on the use of thermography in fruit growing. The method helps control the optimal level of air conditioning and the air flow around fruit and vegetables [6,14,15], control chilled vegetables in storage rooms, and identify deviations at the stage of postripening [22].

The thermal properties of plant leaves depend on the internal structure, which contains a significant amount of water per unit area. Damage by fungi and other microorganisms leads to the drying out of the plant due to enzymatic dysfunction. The spectral absorption bands of water are in the near infrared (IR) range. This allows non-contact thermographic examination of the state of plants due to the versatility, accuracy, and high resolution of RIT. The traditional methods of determining the vegetative parameters of plants are reliable, but costly [11].

Remote measurements with a thermal imaging camera provide the most accurate data on the vegetative parameters of plants compared to the traditional methods.

Stresses and infections (microbial infections, nutritional stresses, insect invasions, droughts) change the surface temperature of plants due to their effect on metabolic processes. RIT allows identifying the plants affected by stress and infection, and studying the process of hydration of plants [23,24].

Many diagnostic methods have been developed. They are used to assess the condition of plants, fruit, and vegetables at various stages of their growth and storage. However, these methods are laborious and do not show quick results. The use of thermography in horticulture and plant growing has not been paid enough attention in scientific works, although this method is easy to use and has good prospects [27-29].

However, a number of works have been published [5,6,13-15,18,22,27-29], where certain issues of the use of thermography in agriculture are considered. The simplicity of the method and new highly sensitive thermal imaging systems significantly expand the range of possible applications of infrared thermography in agriculture. The use of thermography is a topical issue which requires further comprehensive study.

The purpose of the research is to explore new possibilities of using modern thermal infrared systems to monitor the state of vegetables, fruit, and plants during their growth and storage. **The objectives** of the study werer:

- obtain thermographic images of prototypes in order to identify internal damage not seen during external examination;
- to assess whether thermography can be used to determine the process of hydration of plants when they are watered and the presence of internal defects in them;
- to determine the temperature indicators of damaged and undamaged fruit, vegetables, and plants.

Research materials and methods

A domestic infrared thermograph with a matrix photodetector was used for the research. The matrix was cooled with liquid nitrogen, which ensured the temperature measurement accuracy up to 0.07°C. The technical characteristics of the thermograph are described in the authors' paper [19].

The fruit and vegetable samples were taken from vegetable storehouses and analysed in a laboratory environment without an emphasis on a particular variety. The samples were examined for the first signs of rotting. The cultivars considered were as follows: apples – Idared, pear – Bere Kyivska, potatoes – Bellarosa (Bela Rosa), pumpkin – common, or thick-skinned pumpkin.

The quality of fruit and vegetables was assessed based on the registered results of thermal radiation. In the samples without damage, the temperature is distributed uniformly over the entire surface. In the course of spoilage, the temperature in the affected area changes, and RIT allows us to observe it. The thermograms showed areas with temperatures higher or lower than those of the undamaged areas of the samples studied. The extent of damage to the samples under study was assessed by determining the temperature gradient. The temperature gradient is defined as the difference between the temperature in the affected area and the temperature in the area without signs of deterioration.

The plant samples were investigated in the laboratory before and after watering in order to determine the process of hydration of the trunk and leaves. The research object was the Basket plant (*Callisia fragrans*). Thermographic studies were carried out before and after watering the plants, and the hydration of the trunk and leaves was studied in a certain time interval. The results will allow studying how moisture is absorbed by the trunk and leaves, and thus, assessing the condition of a plant. By means of separate samples, it will be possible to determine its condition in the field, too.

Results of the research and their discussion

Fig. 1a shows a thermogram of an undamaged apple. The temperature over the entire surface of the apple is uniform and amounts to 24.52±0.12°C. A thermogram of the initial stage of the deterioration process in the centre of the apple is shown in Fig. 1b, c.

When an overripe apple starts rotting (Fig. 1b), the temperature gradient in the epicentre of destruction changes from 1.56°C to 1.86°C, i.e. we observe a temperature increase in the course of destruction of apple cells.

In Fig. 1c, a thermogram shows us apples at the stage when rotting has developed significantly. The temperature gradient has increased to +2.14°C.

A similar picture is observed when examining the condition of pears.

Fig. 2 shows a thermogram of a pear with a defect on one side (Fig. 2a) and on both sides (Fig. 2b). The temperature gradient in the pear's affected area in Fig. 2a is +0.98°C, and in other areas, the temperature gradient is within the measurement error.

In the pear shown in Fig. 2b, the temperature gradient in the affected area indicated by the number 1 is +1.84°C, and in the affected area indicated as 2, it is +0.77°C. The temperature gradient of the pear beyond the affected area does not exceed the measurement error either.

Potatoes ranks second in the human diet, that is why it is important to preserve the entire harvested crop with minimal losses. When stored in vegetable storehouses, the affected potatoes begin affecting other tubers they are in contact with [22,26]. Therefore, it is important to identify in time the diseased tubers and prevent the spoilage from spreading onto the unspoilt ones.

Fig. 3 shows thermograms of potatoes with no signs of damage. The temperature over the entire surface of the potato in different areas is evenly distributed and varies within ±(0.09–0.11)°C.

Thermograms of potato tubers without damage (a) and at the start of deterioration (b) are shown in Fig. 4. In the zones shown with arrows 1, 2, and 3, the temperature gradients in relation to the unaffected areas are, respectively: ΔT_1=-0.3°C; ΔT_2=-0.29°C; ΔT_3=-2.07°C.

In Fig. 5 (a, b), we observe different degrees of spoilage of the potato tubers.

The temperature of potato tubers, in which the decay process takes place, has different values in the affected area and in the non-affected ones. In the potatoes where the decay process has ended, the difference in the temperatures on the surface and in the affected area is -(0.3–2.07)°C.

In all the figures, the objects of study were placed next to two reference samples to calibrate the thermograph and thus ensure the appropriate measurement accuracy.

A thermogram of a pumpkin with damaged areas is shown in Fig. 6. An external examination revealed no signs of damage. Thermographic studies of the pumpkin showed internal areas of damage resulting from the process of rotting. The temperatures in sections 1, 2, 3, and 4 are, respectively, 28.03°C, 26.78°C, 25.91°C, and 22.17°C.

Thermographic research in plant cultivation.

It is known [13] that the intensity of spectral distributions in the IR range is determined by the molecular vibrations of CH, OH, and NH bonds. As stated above, stress and infection effect on metabolic processes and thus make the surface temperature change. Changes in the temperature of the leaves and the trunk of plants allow using RIT to study the hydration processes that take place when plants are watered.

A thermogram of a plant before watering is shown in Fig. 7a. In 5 minutes after watering, one can observe the movement of the moisture along the trunk of the plant (Fig. 7 b), and in 30 minutes, the moisture already moves about the leaves, too (Fig. 7, c; the arrows point to the moisture in the trunk and leaves).

The fluid distribution in the leaves is not uniform. In the thermograms, we can see that moisture does not spread in certain leaves, which indicates the presence of a plant disease.

The thermograms in Fig. 7d show uniform distribution of moisture in the trunk and leaves. Prior to watering, the temperature in the trunk is 26.93°C, which is below the temperature of the leaves. The temperature of the upper leaves is 27.59°C, and of the lower ones 27.83°C. After watering the plant, we observe a decrease in the temperature of the leaves: 27.21°C in the upper leaves, and 27.34°C in the lower ones.

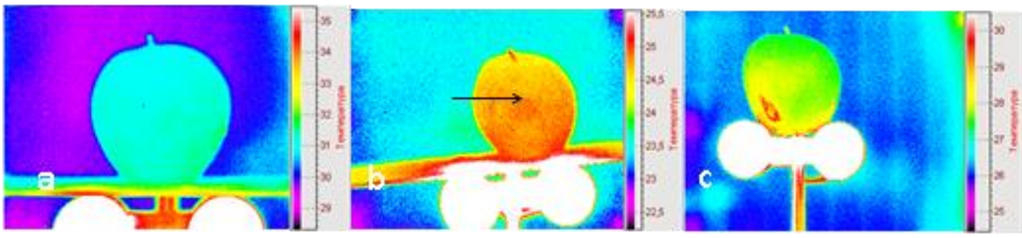

Fig. 1. Thermograms of apples without damage (a) and with damage (b, c)

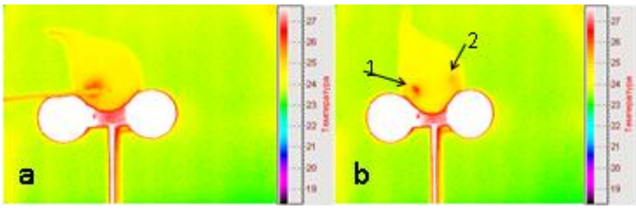

Fig. 2. Thermograms of pears with signs of damage

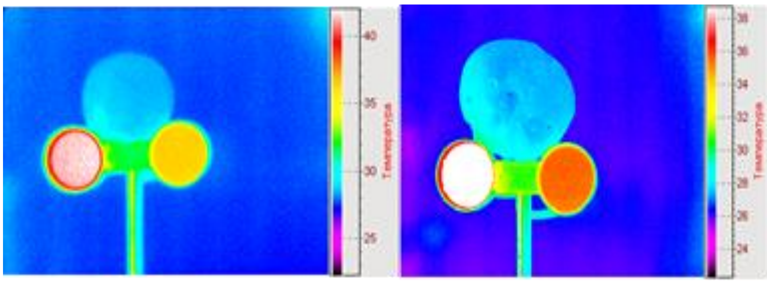

Fig. 3. Thermograms of potato tubers without signs of damage

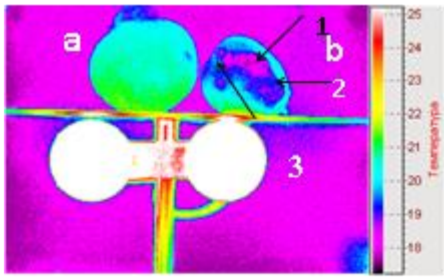

Fig. 4. Thermogram of potato tubers without damage (a) and at the initial stage of deterioration (b); the affected areas are indicated with arrows 1–3

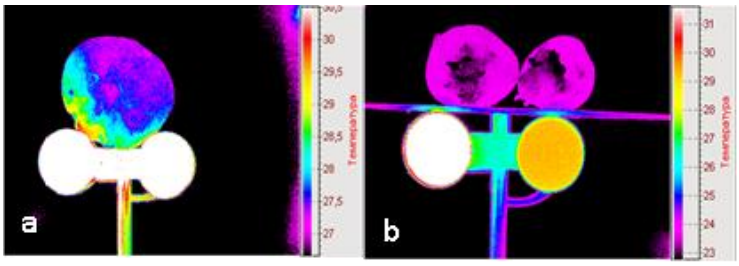

Fig. 5. Thermograms of potato tubers with different degrees of spoilage

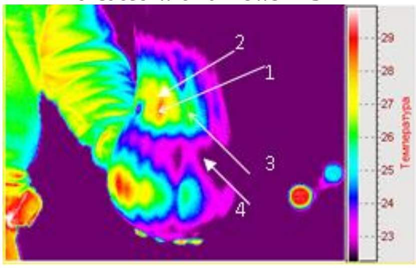

Fig. 6. Thermogram of a pumpkin with a damaged area

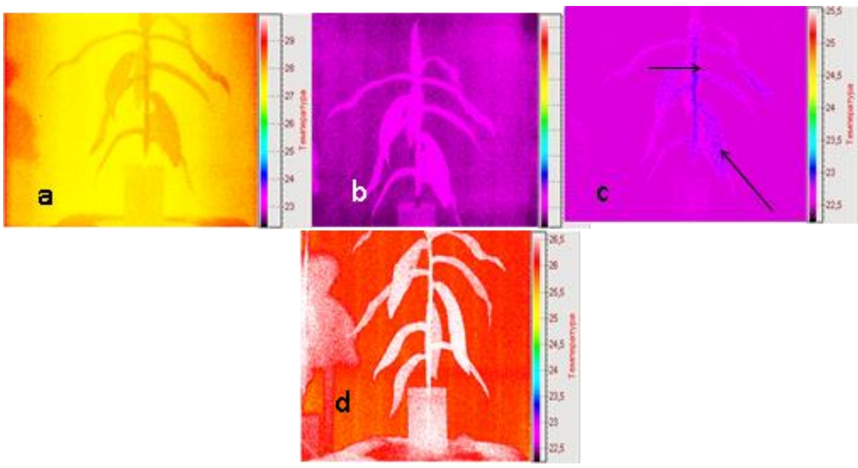

Fig. 7. Thermograms of plants before (a) and after watering (b, c);
b, c – a plant with impaired fluid conductibilty, d – without conductibility disruption

Fig. 7d shows thermograms of a plant without conductibility disruption and with a uniform supply of plant cells with moisture.After the plant is watered, its temperature decreases, and it reaches its initial value in 60 minutes after watering.

Various consumer and sensory properties of vegetables and fruit are determined by their outward appearance. Postripening involves complex processes of heat and mass exchange between fruit and their environment. Spoilage of fruit is accompanied by appearance of zones with an abnormal temperature, which varies from the beginning to the end of the deterioration of the fruit. A ripe fruit without signs of damage has the same temperature over the entire surface with a spread of no more than ±0.12°C. The temperature gradient in the apples where lesions were revealed varied from +1.5°C to +2.14°C. In the pears, there were areas affected in different degrees, and the temperature gradient was, accordingly, +0.74°C and +1.84°C. In the pumpkins, the temperature difference between the unaffected and affected areas reached 5.86°C. In the potatoes, the temperature in the affected area varied from 0.3°C to 2.07°C.

Thermographic observation of the hydration process in plants shows that in healthy plants, moisture is evenly distributed throughout the plant. In diseased plants, moisture spreads along the trunk and in the leaves in a non-uniform manner. Studies like this allow monitoring the condition of plants during their growth and identify in time moisture deviations in plant tissues that can be due to fungal infections.

A comprehensive study of the condition of vegetables, fruit, and plants has been carried out, with determination of the temperature parameters of high-quality and damaged products. It has been shown that infrared diagnostics allows solving a number of problematic issues in the agro-industrial complex.

Conclusion

As a result of the studies, it has been shown that RIT allows, without the use of chemicals and without damage to the objects researched, examining the quality of fruit and vegetables, identifying early centres of spoilage and diseases of fruit and vegetables, and removing the affected products in time, which significantly increases the quality and terms of their storage. A number of thermographic images in the near infrared range of the spectrum 2–5μm have been obtained. They show apples, pears, pumpkins, and potatoes without visible damage and the damaged ones found in the course of the study.

As a result of studying the condition of plants, it has been shown that thermography makes it possible to identify plants with impaired hydration.

The indicators of temperature distribution over the surface of undamaged and damaged fruit and vegetables have been determined.

This article does not address any research using humans and animals as test subjects.

The authors deny conflicts of interest.

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КОНТРОЛЬ СТАНУ ОВОЧІВ, ФРУКТІВ ТА РОСЛИН З ВИКОРИСТАННЯМ МЕТОДУ ІНФРАЧЕРВОНОЇ ТЕРМОГРАФІЇ

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Анотація. Питання визначення якості плодоовочевої продукції та її зберігання є актуальним, про що свідчить значна кількість робіт ближнього та далекого зарубіжжя. У роботах представлено світовий досвід використання різноманітних оптичних методів для інструментальної неруйнівної оцінки зрілості та товарної якості фруктів та овочів. Незважаючи на велику кількість наукових праць, присвячених цій темі, термографічні методи потребують подальшого дослідження та вивчення перспектив застосування сучасних тепловізійних систем в агропромисловому комплексі. У роботі досліджено можливість застосування дистанційної інфрачервоної термографії для контролю за станом овочів, фруктів та рослин в процесі їхнього росту та зберігання. Для визначення якості плодоовочевої продукції шляхом випадкової вибірки досліджувався стан яблук, груш та гарбузів на наявність в них мікробних інфекцій під час гниття, при цьому зовнішніх (видимих) ознак ушкодження не спостерігалось. У лабораторних умовах досліджувались рослини після поливу для визначення процесу оводнення стовбуром та листям з метою оцінки їхнього стану. У дослідженнях використовували матричний інфрачервоний термограф розробки Інституту фізики напівпровідників ім. В.Є. Лашкарьова Національної академії наук України. Дослідження показали, що інфрачервона термографія виявляє внутрішні ушкодження плодоовочевої продукції та дозволяє оцінювати оводнення рослин та їхній стан. Внаслідок виконаної роботи показано, що інфрачервону термографію, як діагностичний метод, доцільно використовувати для своєчасного виявлення внутрішнього розвитку мікробних інфекцій, які призводять до пошкодження овочів та фруктів під час довготривалого зберігання, а також для контролю за станом рослин в процесі їхнього оводнення. Показано, що інфрачервона термографія може бути застосована для контролю якості плодоовочевої продукції перед закладанням та під час довготривалого зберігання з метою своєчасного виявлення ушкоджень, а також в проведенні необхідних досліджень з рослинам в лабораторних та польових умовах.

Ключові слова: інфрачервона термографія, овочі, фрукти, рослини.

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