Celebrating the International Year of Fruits and Vegetables

Non-destructive techniques for mitigating losses of fruits and vegetables

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Técnicas no destructivas para reducir pérdidas en frutas y hortalizas

Técnicas não destrutivas para reduzir perdas em frutas e hortaliças

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Abstract

Fruits and vegetables losses and wastage have massive impacts on the economy, as they constitute about half of the 1.3 billion tons of food annually lost; on the environment, because its elimination generates 10%-12% of greenhouse gases, and on society, because one of every four calories produced is not consumed. Losses are generated during production, postharvest, and marketing periods. In developing countries, only in postharvest, losses reach between 40% and 50% depending on the product considered. Losses can be grouped into physical, biological, and physiological, and their reduction constitutes a challenge that countries are attempting to tackle through both individual and collaborative actions. For applying successful mitigation strategies, not only their quantification but also the identification of factors and occasions in which losses occur are of utmost importance. In this sense, the use of non-destructive techniques is especially useful as such techniques facilitate the detection of physical damages before they are visible or the identification of pathogens before they develop. Other aspects include the possibility of monitoring refrigeration conditions during storage and transport, identifying the occurrence of a cold chain break, and making it possible to rectify the same. In this paper, various techniques applicable to the identification and reduction of losses are reviewed.

Keywords: image analysis, biosensors, temperature monitoring, cold chain

Resumen

Las pérdidas y los desperdicios de frutas y hortalizas tienen un fuerte impacto económico, pues representan alrededor de la mitad de los 1.300 millones de toneladas de alimentos que se pierden anualmente; ambiental, porque su eliminación genera 10-12% de gases de efecto invernadero, y social, porque una de cada cuatro calorías producidas no se llega a consumir. Se generan durante la producción, la poscosecha y la comercialización. En los países en desarrollo, solo en poscosecha, se alcanza entre 40 y 50%, dependiendo del producto considerado. Se pueden agrupar en físicas, biológicas y fisiológicas, y su reducción constituye un desafío al que se abocan los países a través de acciones tanto individuales como colaborativas. Resulta de suma importancia no solamente su cuantificación, sino la identificación de causas y momentos en los que se producen para aplicar medidas de mitigación. En este sentido, el uso de técnicas no destructivas resulta de gran utilidad ya que, por ejemplo, permitiría identificar daños físicos antes de que sean visibles o identificar patógenos antes de que se desarrollen. Otro de los aspectos es la posibilidad de monitorear condiciones de refrigeración durante el almacenamiento y el transporte, identificando la ocurrencia de ruptura de cadena de frío y posibilitando su corrección. En este trabajo se revisan algunas de las técnicas disponibles aplicables a la identificación y la reducción de pérdidas.

Palabras clave: análisis de imágenes, biosensores, monitoreo de la temperatura, cadena de frío

Resumo

As perdas e desperdícios de frutas e hortaliças têm forte impacto econômico, pois representam quase a metade dos 1.300 milhões de toneladas de alimentos perdidos anualmente; ambiental porque sua eliminação gera de 10 a 12% dos gases de efeito estufa; e social porque uma em cada quatro calorias produzidas não é consumida. Acontecem durante as etapas de produção, pós-colheita e comercialização. Nos países em desenvolvimento, apenas na pós-colheita, atingem entre 40-50% dependendo do produto. Podem ser agrupadas em físicas, biológicas e fisiológicas, e sua redução constitui um desafio que os países estão enfrentando por meio de ações individuais e colaborativas. Não só a sua quantificação é extremamente importante, mas também a identificação das causas em momentos em que ocorrem para a aplicação de medidas de mitigação. Nesse sentido, o uso

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de técnicas não destrutivas é muito útil, já que por exemplo, permitiria identificar danos físicos antes que sejam visíveis ou identificar patógenos antes do seu desenvolvimento. Outro aspecto é a possibilidade de monitorar as condições de refrigeração durante o armazenamento e transporte, identificando a ocorrência de quebra da cadeia de frio e possibilitando sua correção. Neste artigo são revisadas algumas das técnicas não destrutivas disponíveis e aplicáveis à identificação e redução das perdas.

Palavras-chave: análise de imagens, biosensores, monitoramento de temperatura, cadeia de frio

1. Introduction

Fruits and vegetables can be subjected to *loss* and/or *wastage*. Such terms and their meanings are different, but both confirm that the product quantities that had been originally estimated do not ultimately reach the destination. Both refer to products intended for human consumption, differing by the time when they are produced. Losses can occur during any phase of the production chain (production, post-harvest, processing and/or storage) before the product reaches the commercialization phase. Wastage, which refers to the elimination of food suitable for consumption from the supply chain or food that has been spoiled because of economic issues, mismanagement of stocks or negligence, occurs in the phases of sale and consumption[1].

One-third of the food intended for human consumption, which is equivalent to 1.3 billion tons per year, is lost or wasted. For cereals, this number represents 30%, and in tubers, fruits and vegetables it is between 40%-50%. In terms of calories, it implies that one out of every four produced items is not consumed, which becomes serious when considering that the number of undernourished people is increasing, reaching 690 million in 2019 —10 million more than in 2018 and 60 million more than five years ago[2]. According to forecasts, the situation would worsen because of the Covid-19 pandemic, as between 83 and 132 million undernourished people could be added to this list. In terms of costs, they are close to a trillion USD a year, where 700 billion USD correspond to environmental costs and 900 million USD to social costs[3].

Losses and wastage indicate that the product is not available for consumption and there is loss of resources destined for its production, such as water, energy, agrochemicals. Furthermore, losses and wastage elimination generate greenhouse gas emissions (between 10%-12% of total emissions), responsible for climate change, which are increasing, going from 540 to 1,600 megatons between 1960 and 2011. To this magnitude, it is vital to add the emissions associated with its production, which tripled in the same period, from 680 to 2,200 megatons of CO_2. The largest increase in greenhouse gas emissions corresponds to the increasing losses and wastage corresponding to developing economies, specifically China and Latin America, and is mainly linked to losses that occur in the fruit and vegetable chains[4][5].

During the production stage, losses occur because of a number of factors, including losses of quality and quantity linked to changing climatic conditions; changes in tastes and/or market demands that lead to many products not even being harvested; social changes in the productive sector, mainly the increasingly pronounced lack of labor; bad management practices such as fertilization, irrigation, phytosanitary application at inappropriate times, doses and/or active ingredients, among others[6][7].

During the postharvest period, losses are of different origins and can be grouped into (i) physical, those produced by mechanical agents that impact directly on the appearance and constitute a pathway for the entry of pathogens; (ii) biological, associated with biotic agents as fungi, bacteria, virus, and insects, and that affect the quality directly or indirectly (e.g., mycotoxin contamination); and (iii) physiological, those associated with the normal (conducive to the senescence) and/or abnormal metabolic processes, resulting in the metabolism alteration as a consequence of the inadequate management of

storage, mainly linked to the temperature and/or atmospheric composition[8][9][10].

2. Loss reduction

The first step to achieve postharvest loss reduction is to identify and quantify it within each production system. Quantification implies not only determining the value of the losses themselves, but also quantifying the costs that were incurred during the production (preharvest period). Furthermore, the knowledge of losses (causes and times when they occur) allows the adoption of appropriate strategies for its reduction. These actions include the improvement of practices in both harvest and postharvest as carefully handling, harvesting at the appropriate maturity stage, washing and disinfection of utensils and containers, avoiding mechanical damage (such as bruises); the management and improvement of the storage conditions, especially with regard to the use of the adequate temperature (knowledge of their physiology), and the management of relative humidity; and the improvement of logistics during transport and marketing at points of sale, among others.

The development of non-destructive techniques (obtaining chemical and physical data simultaneously through non-invasive techniques and therefore without any effect on the appearance and quality), such as image analysis or the determination of compounds through biosensors and temperature monitoring through sensors, enables decision-making before the occurrence of losses, such as marketing the products before pathogens develop or deterioration symptoms appear.

Here are some examples of application of mitigating the different kinds of losses.

2.1 Reduction of physical losses

Losses due to the physical damage are one of the most predominant in the fruit and vegetable production, considering that appearance is the main purchase criterion for fruits and vegetables, which according to studies has a weight of 83% in the election. Furthermore, the presence of physical damage like wounds, but mainly bruises, many times conditions the purchase much more than the price of the

product itself[11]. Physical damage not only represents a loss in itself, because of rejection at the consumer level, but also because of the acceleration of metabolism (respiration rate and ethylene emission), dehydration, increased susceptibility to rotting and/or reduction of functional and nutritional value (loss of overall quality).

Investigations conducted on fruits and vegetables indicate that between 30% y 40% of fruits and vegetables suffer some type of mechanical damage, mainly bruises, from harvest to marketing[12]. The development of methods that allow the detection, measurement, and analysis of mechanical damage is considered to be the first step to work on reduction[13][14]. Bruises occur because of excessive pressure on the surface of the product, which determines the breakdown of cellular structures and the occurrence of enzymatic reactions that lead to the development of sunken and dark spots. These spots are not immediately visible because they have a variable incubation time (12 h or more) and are usually noticed during the commercialization stage. Bruises occur when products impact on each other or on hard surfaces, what can occur at harvest, packing, and/or during transportation[15][16].

Studies related to bruising reduction are predicated on the establishment of correlations between the level of damage and mechanical parameters such as force, fall height, impact speed, acceleration, and absorbed energy. It has been determined that there is a linear correlation between the size of the damage and the energy absorbed. Excessive mechanical energy during contact, either by compression or by impact, determines the appearance of damage[17].

There are different approaches for early detection of bruise damage, including biochemical and physical methods. The former ones are based on the measurement of metabolites (structural carbohydrates, phenolic compounds) and/or enzymes (polyphenol oxidase, polygalacturonase, pectin methyl esterase, lipoxygenase) released by damage, and have the disadvantage of being destructive and costly in terms of time and money. The latter ones include firmness/texture analysis, acoustic response, mechanical resonance, and optical methods such as ultrasound, X-rays, gamma rays, magnetic

resonance, fluorescence, reflectance, transmittance, dielectric properties, thermal emission, among others[18].

Non-destructive determination applied to the vegetables products includes spectroscopy, which studies the interaction that is established when electromagnetic radiation interacts with matter, causing the absorption or emission of radiant energy. It is used mainly to determine components (sugars, acids, etc.), and to identify defects, mainly using radiation in the visible (VIS 400-700 nm) and in the near infrared (NIR, 780-2500 nm) range. In addition, it constitutes a tool for selecting the bands to be used in hyperspectral and multispectral vision systems[19].

Hyperspectral imaging is an emerging technique that integrates conventional imaging and spectroscopy to extract spatial and spectral details of an object. A noteworthy advantage of a hyperspectral imaging system is its ability to incorporate both spectroscopy and imaging techniques to simultaneously perform a direct evaluation of the different components and locate their spatial distribution in the products being evaluated. This system is used successfully to detect bruises in potatoes, pears and apple varieties with a detection level of 90%-100%[20]; however, it is not efficient in the bicolor varieties. In this case, multispectral vision systems are used, where, instead of obtaining images in all the wavelengths of the spectrum, only a few are selected, generally no more than 20, that may not even be adjacent. Wavelengths for such systems depend on the product[21]. For example, in tomatoes, bruise damage is detected at 810 nm, in apple 760, 850, and 960 nm, and in pear at 526-824 nm[21][22][23].

Fluorescence imaging systems are based on the fundamental principle that organic materials emit a unique fluorescence when excited by a particular electromagnetic radiation or visible light[24]. For bruise detection, the base is that fruits have a high content of chlorophyll, which could fluoresce between 685 and 730 nm, but when they experience a bruise, the chlorophyll is destroyed, and the fluorescence excitation is reduced compared to that of a healthy tissue[25][26]. This characteristic means that this technique can only be used in fruits with chlorophyll and with a thin peel, as kiwifruit, pear, and apple. However, it allowed detecting bruise damage on apple 0.5 h after the damage occurred with 86.7%, and after 1 h with 100% accuracy, and before the damage was visible to the naked eye[25]. The limitation for its application in process lines would be given by the time it takes to process the images, which is around 78 s[20].

To prevent the occurrence of bruise damage, a series of instruments containing accelerometers or pressure sensors that mimic the physical properties and mechanical responses of vegetable products have been developed[27]. They are known as electronic spheres or pseudo fruits, which are wireless data loggers that when placed on the lines suffer the same mechanical stress as the fruits, giving information about the place of occurrence and the magnitude[14]. One of the most used is the IS 100, developed by researchers at the University of Michigan. This instrument uses a triaxial accelerator as a shock sensor that records acceleration and speed information. The first prototype was a 140 mm sphere, the second generation was an 89 mm sphere, and the latest version —called the impact recording device (IRD)— is a sphere with a diameter of 57 mm and a weight of 96 g[28]. There are also other devices with ellipsoid shapes that are used to evaluate impacts on potatoes (PTR 1100), onions (PMS-60), and berries (BIRD), among others[29][30].

2.2 Reduction in pathogenic losses

Traditionally, control of pathogens, both in the field and postharvest stage, has been carried out using chemical products. However, because of the growing interest in reducing waste and consumer pressure, physical and biological control methods are becoming increasingly important[31][32][33]. Controlling pathogens involves a series of procedures that may even begin during the cultivation period, since many of them can remain latent and develop when the maturity process makes the vegetable tissues easier to colonize.

Therefore, it is important to have tools that can perform early detection even before the symptoms and/or signs for pathogens appear, as with this information, it would be possible to separate batches, preventing the development and spreading of diseases on storage structures, and/or deciding to market these products before they deteriorate. For

a timely detection of disease-causing microorganisms, the use of biosensors is a promising tool[34].

Biosensors are a type of chemical sensors that are formed by a biological element for recognition (enzyme/substrate pair; antibody/antigen; nucleic acid/complementary sequence), by nanomaterials (nanoparticles, nanocomposites) or by biomimetic compounds (aptamers, intrinsic microporosity polymers, nucleic acid probes). These last are devices capable of recording the variations of some measurable property (optical, physicochemical, electrical) that appears when the analyte and the device interact. In addition to the biological element, biosensors consist of a transducer that can be electrochemical, optical, thermal, piezoelectric, or magnetic[35][36]. In an optical biosensor, as a response to the physical or chemical change that occurs in the biorecognition process, there are changes in the amplitude, polarization, or frequency of the input light. The main components of an optical biosensor are a light source, an optical transmission medium, an immobilized biological recognition element (enzymes, antibodies, etc.), and an optical detection system. They are selective and specific remote sensors that can perform measurements in real time. They are classified according to the optical effect on which they are based, which can be fluorescence, chemiluminescence, or surface plasmon resonance[37][38].

In electrochemical biosensors, the biological biomolecule that is formed in the recognition element is transformed into an electrical signal in the transducer. Electrochemical biosensors can be classified into amperometric, potentiometric, impedimetric, and conductometric, depending on the electrical parameter on which they are based, whether current, potential, impedance, and conductance, respectively. One of the reasons for their popularity is their use of simple analytical methods and low cost[37][38].

Piezoelectric biosensors function by detecting changes in mass. By applying an electrical signal of a specific frequency, piezoelectric crystals vibrate at a specific frequency. The frequency of oscillation, therefore, depends on the electrical frequency applied, the characteristics of the crystal, and the crystal's mass. Therefore, when the mass increases because of the binding of chemicals, the frequency of the crystal oscillation also changes, and the

resulting change can be electrically measured. This electrical signal determines the additional mass of the crystal[39].

There are also biosensors based on the detection of volatiles equipped with specific tubes that separate a specific gas from the air for analysis. These biosensors are used both at the field level, to detect diseased plants, and in storage structures such as potato storages, for example[38][40].

2.3 Reduction in physiological losses

Temperature reduction is the main tool to maintain the shelf life of fruits and vegetables, thereby allowing the access to safe products of good organoleptic, functional, and nutritional quality. Low temperatures facilitate the metabolism, respiratory activity, and ethylene emission reduction, in addition to the reduction in the number of microorganisms that cause spoilage (fungi and bacteria) growth, and the speed of browning reactions and water loss[41][42].

The extension of the use of refrigeration has made it possible to apply it in the supply chains of plant products. Today, these chains, called cold chains, are globally prevalent and allow the transport of billions of tons of products between regions, countries, and continents. The term *chain* emphasizes the importance of temperature control in the different stages or links: packing plants, storage chambers, transportation, chambers, and showcases of wholesalers and retailers, and even domestic refrigerators. In the cold chain concept, any failure in the temperature in a link can lead to the loss of the product. These faults, known as outages, breaks, abuse, interruptions, or spikes, can have different causes, such as cooling system outages, incorrect temperature settings in the cooling systems, highly uneven temperature distribution due to uneven air distribution or exposure to ambient air during delivery loading and unloading[43][44]. According to a review of the theme in question, there are studies linked to the maintenance of the cold chain in various types of products (meat, fish, fruits and vegetables), and evaluations of losses using various criteria: health risks, effects on sensory characteristics, vitamins, and shelf life. Depending on the type of product, two-hour cold chain breaks can reduce shelf life by 10%-40%[45]. For highly perishable products, the occurrence, the level at which the cold chain break

occurs, and the duration can have a great impact on the quality determining even total losses. Therefore, maintaining the cold chain from harvest to sale is one of the fundamental points to reduce losses. However, in real situations, this is not always feasible, so monitoring and knowing in real time what happens during storage and transport (temperature, humidity, or any other relevant parameter such as respiration and/or ethylene emission) become essential in advanced logistics[46][47]. One of the practices used to detect breaks in the cold chain consists of measuring the temperature in different positions on a pallet. However, as it is a localized measure, it does not provide a clear idea of the temperature variations within the pallet or within the load of a chamber or refrigerated transport, which is known to be highly irregular, and being a measure at a certain time, it does not also allow to know if and when the previous ruptures occurred[48]. A wide array of technologies has been developed to record, transmit, and access this type of data in real time throughout the cold chain, with the possibility of sending a warning signal in the event of temperature abuse. Today, with the emergence of Internet of Things, wireless temperature sensors, wireless sensor networks (WSN), and radio frequency identification (RFID) technology have allowed the measurement and transmission of temperature in real time to web platforms[49][50][51]. To these are added the temperature estimation methods, thermal imaging, and computational fluid mechanics, among others[52][53].

RFID is an identification system that uses radio frequency and belongs to Auto ID systems that include smart cards, barcodes, optical recognition systems, among others. An RFID system is made up of a tag or tags that, depending on its energy source, is classified as passive, semi-passive or active, and according to its working frequency, as low, high or ultra-high frequency. The passive cards do not have power; the semi-passive cards have a battery, but only the circuit remains in operation, and the active cards have a battery that also allows them to transmit the information. The other constituent elements are the RFID reader, responsible for reading and interpreting the data stored by the cards, and finally a computer with the database and the program to manage them[54][55]. There are RFID cards with both active and semi-passive temperature sensors, and other types of sensors are being developed. The technologies that allow both producers and retailers to record, transmit, and access data in real time are based on RFID, satellite communication, and data accumulation in the cloud, but there are still certain technological and economic challenges that need to be resolved[47][56].

Deviations from optimal conditions or of the expected arrival time will be incorporated into the expected expiration time models. WSNs consist of small, low-power, low-cost autonomous devices that perform monitoring tasks. That is, they can measure certain parameters of their environment and transmit them wirelessly to a station where the data are stored[57]. Comparatively, WSNs have a greater capacity to collect data than RFIDs as they incorporate humidity, pressure, luminosity sensors, etc., in addition to temperature. They can also use "multi-shop" communication to adapt to the presence of obstacles. There are a number of works where both systems are used and in which the advantages of their collective use are underlined in comparison to their individual use[53][58][59].

3. Conclusions

Due to economic, social, and environmental factors, it is imperative to work to reduce the losses of fruits and vegetables throughout the production chain. This process includes simple practices that can be readily extrapolated to production systems, like carrying out good harvesting practices such as not hitting the fruit, protecting it from the sun, among others, to more complex practices that involve the use of non-destructive techniques, such as sensors for the separation of batches in the warehouses, or WSNs for the monitoring of transport and storage, especially in the anticipated determination of the alterations that allow to take measures before the products are lost. Notwithstanding the differences and the possibilities of application, all of them have their validity and importance, and ideally, they should be used together to achieve a greater impact on the reduction of losses.

Author contribution statement

All authors contributed equally to the content.

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