processes

MDPI

Review

Recent Advances in Reducing Food Losses in the Supply Chain of Fresh Agricultural Produce

Daniel I. Onwude [1,2,*], Guangnan Chen [3], Nnanna Eke-emezie [4], Abraham Kabutey [5], Alfadhl Yahya Khaled [6] and Barbara Sturm [7]

1 Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland
2 Department of Agricultural and Food Engineering, Faculty of Engineering, University of Uyo, Uyo 52021, Nigeria
3 Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, QLD 4350, Australia; Guangnan.Chen@usq.edu.au
4 Department of Chemical and Petroleum Engineering, Faculty of Engineering, University of Uyo, Uyo 52021, Nigeria; nnanna.chimaobim@gmail.com
5 Department of Mechanical Engineering, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague, Czech Republic; kabutey@tf.czu.cz
6 Department of Biosystems & Agricultural Engineering, College of Agriculture, Food and Environment, University of Kentucky, Lexington, KY 40503, USA; Alfadhl.Alkhaled@uky.edu
7 Process and Systems Engineering in Agriculture Group, Department of Agricultural and Biosystems Engineering, University of Kassel, DE-37213 Witzenhausen, Germany; Barbara.sturm@uni-kassel.de
* Correspondence: daniel.onwude@empa.ch

Received: 12 September 2020; Accepted: 5 November 2020; Published: 9 November 2020

Abstract: Fruits and vegetables are highly nutritious agricultural produce with tremendous human health benefits. They are also highly perishable and as such are easily susceptible to spoilage, leading to a reduction in quality attributes and induced food loss. Cold chain technologies have over the years been employed to reduce the quality loss of fruits and vegetables from farm to fork. However, a high amount of losses (≈50%) still occur during the packaging, pre-cooling, transportation, and storage of these fresh agricultural produce. This study highlights the current state-of-the-art of various advanced tools employed to reducing the quality loss of fruits and vegetables during the packaging, storage, and transportation cold chain operations, including the application of imaging technology, spectroscopy, multi-sensors, electronic nose, radio frequency identification, printed sensors, acoustic impulse response, and mathematical models. It is shown that computer vision, hyperspectral imaging, multispectral imaging, spectroscopy, X-ray imaging, and mathematical models are well established in monitoring and optimizing process parameters that affect food quality attributes during cold chain operations. We also identified the Internet of Things (IoT) and virtual representation models of a particular fresh produce (digital twins) as emerging technologies that can help monitor and control the uncharted quality evolution during its postharvest life. These advances can help diagnose and take measures against potential problems affecting the quality of fresh produce in the supply chains. Plausible future pathways to further develop these emerging technologies and help in the significant reduction of food losses in the supply chain of fresh produce are discussed. Future research should be directed towards integrating IoT and digital twins for multiple shipments in order to intensify real-time monitoring of the cold chain environmental conditions, and the eventual optimization of the postharvest supply chains. This study gives promising insight towards the use of advanced technologies in reducing losses in the postharvest supply chain of fruits and vegetables.

Keywords: food security; food quality; agricultural production; crop storage and processing; food distribution; smart digital technology; industry 4.0; refrigeration

1. Introduction

Food losses in the postharvest supply chain amount to a great loss of investments in the packaging, transportation, and storage operations. About 25–30% of global food produced is lost between on-farm food production and its storage at a retail facility, largely as a result of poor chain management and spoilage [1,2]. Food losses occur due to a reduction in quality and safety standards driven by consumer preferences, particularly in developed countries [3]. A high amount of losses (up to 30% per year) is often experienced during the postharvest handling of fresh agricultural produce, such as fruits and vegetables [4]. Advanced technologies are required to reduce the losses of fruits and vegetables in the postharvest supply chain. The reduction of these losses would increase the number of fresh produce available for consumption.

Fruits and vegetables are important sources of nutrients such as vitamins, minerals, and bioactive compounds, which provide many health benefits [5–8]. However, they are highly perishable goods that need to be appropriately preserved, to reduce the degradation of macro and micro-nutrients and extend shelf life [7,9,10]. As a result, fruits and vegetables are often packaged and kept in a desired low-temperature range using various refrigeration systems during the transportation and storage postharvest handling processes. This process delays or reduces microbial growth and enzymatic reaction, thereby improving overall quality, reducing mass loss, and extending shelf-life. The succession of refrigeration steps along these chains can be referred to as a postharvest cold chain of fruits and vegetables [11]. A description of the postharvest cold chain of fruits and vegetables is shown in Figure 1.

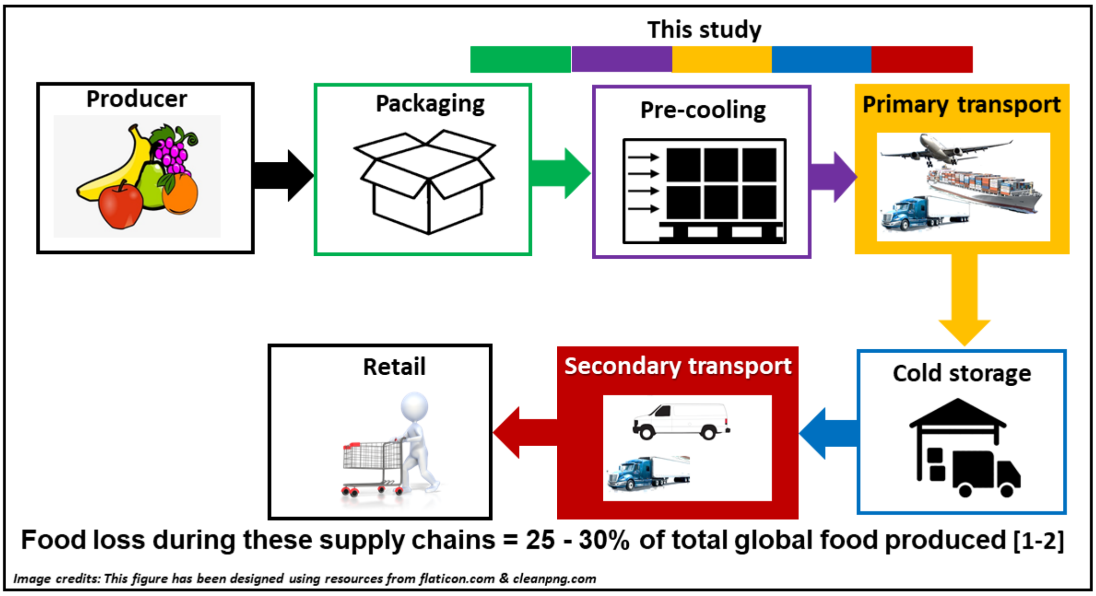

Figure 1. Postharvest refrigerated supply chain of fruits and vegetables.

Refrigeration is a key element in enhancing the quality of fresh produce and extending the shelf-life, thereby enabling their adequate supply to an increasingly urbanized world [11–13]. However, more than 90% of perishable goods are still not refrigerated [1,14]. Inadequate refrigeration infrastructure or access to energy accounts for more than 20% losses of perishable goods [15]. These losses also encompass a huge amount of energy and water losses, but also carbon dioxide emissions [15,16]. Therefore, sustainable cold chain technologies in terms of being more resource-efficient, improving product quality retention, and reducing induced food losses become indispensable.

Several studies have been conducted on the postharvest cold chain of fruits and vegetables with a view to gain more insight on ways to address these technological and developmental challenges. The losses in the mass and nutritional qualities of strawberries, raspberries, red currants, drupes, cherries, and sour cherries were reduced using refrigerated containers at 4 °C when compared to storage at room temperature [17]. Packaging methods such as edible coating, active modified atmosphere packaging (MAP), nano-composite based packaging (NCP), and polypropylene/polyethylene bags have been used to reduce quality losses of cherry tomato, kiwifruits, guava, mushroom, cucumber, and berries during cold chain processes [18–23]. Recently, active packaging such as oxygen scavengers, ethylene absorbers, moisture regulators, and intelligent packaging including the use of chemical sensors, temperature, freshness and gas indicators, barcodes and radio frequency identification devices (RFID), have been developed to maintain the quality and improve the safety of fresh produce [24–27]. These different packaging methods are simple to design, easily affordable and can help to extend product shelf life [15]. However, retailers in the food supply chain are increasingly looking for ways to minimize or eliminate the use of packaging, to project sustainable eco-friendly products [28]. Consequently, the negative impact of most packaging materials (e.g., plastic packaging) is largely overestimated by consumers in comparison to other actions with much higher impacts [29–31]. As an example, the controversy between paper bags versus plastic packaging comes to mind. Paper bags hold a much higher environmental impact, due to its higher weight [32], but are often perceived to be more eco-friendly by the consumer. In a similar manner, a life cycle analysis of a commonly consumed fruit or vegetable with and without packaging will show that the environmental impact of plastic packaging, for example, is by far smaller than the impact of the food losses [33,34]. In addition, plastic packaging presently reduces food losses by up to 4.8% at retail and also reduces induced food losses at households as a result of prolonged shelf life [35]. Despite all these improvements and awareness from peer-reviewed literature, the question of why a significant amount of food losses in the postharvest supply chain (see above) arises, suggesting that more insight and advances into cold chain technology are required to further reduce food losses by preventing excessive quality loss of fresh produce.

Key drivers that accelerate food losses during the postharvest supply chain of fruits and vegetables include lack of innovative packaging materials, inadequate monitoring technology, variations in the temperature, approach air velocity and relative humidity in cold chain systems, rate of metabolism, long shipment duration and the heterogeneity of fruits and vegetables. During shipments, there is often a wide variation of temperature and relative humidity at different locations in a cold chain system. Great variations in the approach airspeed of different fruits and vegetables are often observed as a result of the heterogeneous nature of refrigeration equipment, food properties, and packaging container. These variations can affect the final mass loss, overall quality, and the remaining shelf life of fresh produce [36–38].

Understanding the physics behind different phenomena that occur during the different postharvest supply chains and linking these phenomena to measurable output using sensors that provide actionable data may be the key in optimizing the design of packaging, storage, and transport processes for fruits and vegetables. Unfortunately, studies on these advances are limited.

This paper aims to explore ways on how food losses can further be reduced in the postharvest supply chain of fruits and vegetables. Particularly, we discuss the current state-of-the-art in monitoring and optimizing cold chain systems for a reduction in quality loss during the packaging, transportation, and storage of fruits and vegetables. We also analyze the potential of applying emerging technologies such as the Internet of Things (IoT) and digital twins for reducing food losses. We then put forward how the future should look towards reducing food losses during the packaging, storage, and transportation supply chain.

2. The Need to Reduce Food Losses in the Postharvest Supply Chain of Fruits and Vegetables

Food losses can be referred to as "the reduction in the amount of fresh fruits and vegetables that was originally meant for human consumption" [39–41]. Globally, one third to half of all food produced is lost or wasted along postharvest supply chains, with packaging, storage, and transportation value chains the most impacted [42,43]. Losses of fruits and vegetables worldwide are between 40% and 50% of which 54% occur in stages of production, postharvest handling, and storage [3,44,45].

During packaging, transportation, and storage of fresh agricultural produce, food losses are often induced as a result of a reduction in the quality (e.g., color, texture, mass) of the produce. These postharvest handling operations affect the nutritional and sensory quality of the agricultural produce, the mass of the fresh produce as well as the quantity of fresh produce available to the consumers. The quality of fresh agricultural produce can be referred to as the excellent characteristics of such products that are acceptable to a consumer [46]. Consumers typically purchase fresh agricultural produce based on their biochemical characteristics such as appearance, texture, flavor, and nutritive value [46,47]. Fresh agricultural produce such as fruits and vegetables provide an essential part of human nutrition, as they are important sources of vitamins, dietary fibers, minerals, and other biochemical (e.g., carbohydrate, protein, etc.) with tremendous health benefits [48]. Adequate in-transit monitoring of environmental conditions and changes in the quality attributes of fresh produce during transport and storage will help reduce food losses and ensure the availability and accessibility of fresh fruits and vegetables with high nutritional density to the consumers [49,50]. Therefore, emerging technologies are needed to help reduce the overall quality loss of fresh agricultural produce, thereby reducing food losses in the postharvest supply chain.

3. Advanced Technologies for Quality Assessment in Postharvest Supply Chain: State-Of-The-Art

In recent decades, several modern food quality techniques have been applied to monitor, control, and predict the quality evolution of various fruits and vegetables in postharvest supply chains. These techniques include imaging systems, spectroscopy, multi-sensors, electronic nose (E-nose), acoustic impulse response (AIR), radio frequency identification (RFID), printed sensors (PTS), and mathematical modeling. In this section, we analyze the application of these techniques in advancing cold chain operations and process optimization during the packaging, storage, and transportation of fruits and vegetables within the past 10 years.

3.1. Application of Imaging Technology, Spectroscopy, Multi-Sensors, E-Nose, AIR, RFID and PTS in the Postharvest Supply Chain of Fruits and Vegetables

Imaging technology is an advanced method used by the food and agro-allied industries to monitor changes in food quality [51]. This technology includes computer vision (CV), hyperspectral imaging (HSI), multispectral imaging (MSI), thermography, and X-ray imaging. Image technology is particularly useful in detecting and evaluating the external quality attributes (color, geometrical, size, appearance, and surface structure) [52,53], and in some cases, the internal structures (X-rays and hyperspectral imaging) of fruits and vegetables. This technology involves collecting and analyzing spatial information gained from captured images of products, such as color, geometrical, size, appearance, and surface structure. The application of imaging technology in postharvest supply chains is mainly limited to surface detection. The surface properties of an object can be detected due to the interaction of light. A typical imaging system consists of a CCD camera, a light source, a computer, and related software (Figure 2). The camera captures the images of the product based on the region of interest. The captured images are then processed to evaluate and quantify the quality changes that have occurred during a particular postharvest operation. The image processing steps often consist of image acquisition, segmentation, feature extraction and recognition, classification, and interpretation [54–57].

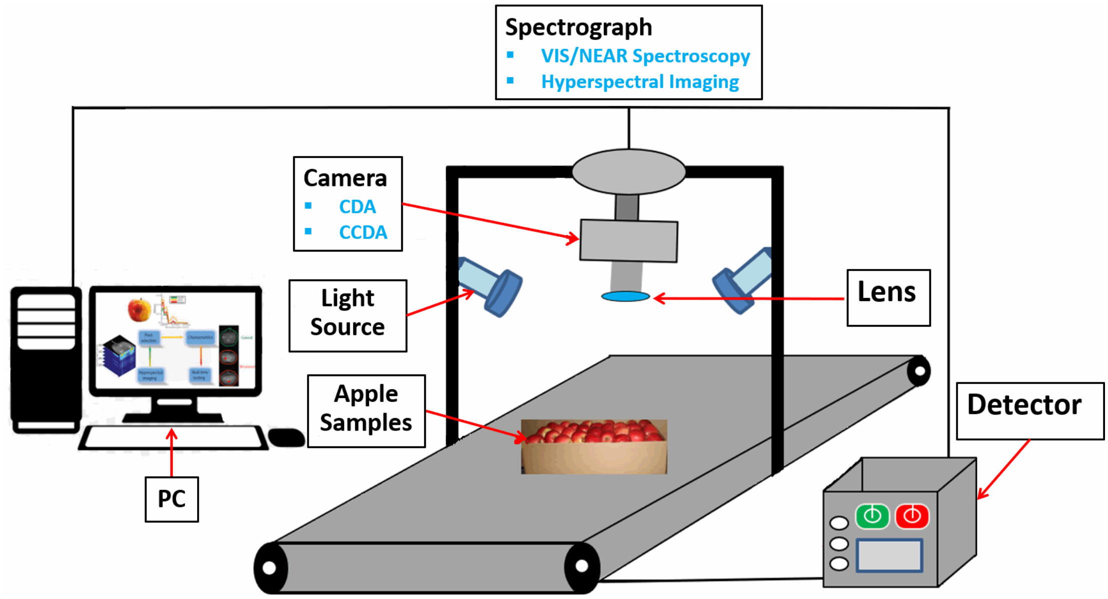

Figure 2. Typical set-up of an imaging system for monitoring the quality of fresh agricultural produce.

In order to adequately discriminate and analyze the captured numerous images, chemometrics and deep learning methods are often employed. These methods have already been found reliable in quantifying the accuracy of processed images and associated quality changes of fruits and vegetables in the postharvest supply chains (Table 1). They include Savitsky–Golay (SG), Standard Normal Variate (SNV), Principal Component Analysis (PCA), Partial Least Squares Regression (PLSR), Multiple Scatter Correction (MSC), Partial Least Squares Discriminant Analysis (PLS-DA), Artificial Neural Network (ANN), Convolutional Neural Networks (CNN), Linear Discriminant Analysis (LDA), k-Nearest Neighbors (kNN), Correlation-based Feature Subset Selection (CFS), Gini Impurity Algorithm (GIA), Sequential Forward Selection (SFS), Backpropagation Neural Network (BPNN), Extreme Learning Machine (ELM), Sparse Logistic Regression (SLR), Support Vector Machine(SVM), Radial Basis Function (RBF), Neural Networks (NN), Genetic Algorithm (GA), Support Vector Regression (SVR), Student–Newman–Keuls (SNK), Least Squares Support Vector Machines (LS-SVM), and Random Forest (RF).

The applications of different imaging and smart digital technologies in monitoring the quality of fruits and vegetables in postharvest cold chains are summarized in Table 1. These technologies include computer vision (CV), hyperspectral imaging (HSI), multispectral imaging (MSI), X-ray imaging, spectroscopy, multi-sensors, E-nose, and acoustic impulse response.

From Table 1, the majority of the study was done using CV [58–66]. This involves the capturing of images of a product using a digital camera, and the ability of computers to understand the processed image data using computational intelligence tools (e.g., chemometrics, deep learning) [54,55]. This imaging method is rapid, reliable, and consistent. However, this technique has some limitations such as the use of artificial lighting during image capturing and the inability to detect internal attributes. Table 1 further shows that the bulk of the studies using CV was on cold storage, mostly to monitor and detect spoilage, chilling injury, and shelf-life of grapes, lettuce, tomato, zucchini, banana, strawberry, oranges, and mango [58–64,66]. CV with several chemometric and statistical analytic approaches was able to quantify quality losses with 75–92% accuracy (Table 1). Only a single study explored the application of CV in quantifying the quality losses of lettuce as a result of packaging material used, with 86% accuracy (Table 1) [65].

Hyperspectral and multispectral imaging (HSI and MSI) are advancements of computer vision, which involves the capturing of image data at a different wavelength (e.g., continuous 400–1700 nm in steps of 1 nm for HSI and targeted 400–1100 nm in steps of 20 nm for MSI) across the electromagnetic spectrum [67–70]. Hyperspectral imaging particularly integrates both imaging and spectroscopy features to simultaneously gather spectral and spatial information from a product, thus making it a more powerful imaging technology compare to CV and multispectral imaging [71]. Both hyperspectral and multispectral imaging technologies can detect internal and external quality attributes of fresh produce. However, they also require artificial lightning, are very sensitive to environmental conditions, have limited penetration depth, and are very expensive to use. Closely following CV, several studies have been conducted on the application of hyperspectral imaging in monitoring the quality of spinach, mushrooms, cucumber, mango, apples, and citrus fruit during cold storage and packaging (Table 1) [72–75]. This imaging system coupled with PCA, CFS, GIA, SFS, SLR, LDA, kNN, and NN was able to give 89–98% accuracy (Table 1). However, not so much for multispectral imaging, as only two studies quantified the quality losses of mangoes during the cold storage, with a classification rate of ≈92% using PLS-DA (Table 1) [70,76].

Spectroscopy, which is the study of the interaction of electromagnetic waves, including ultraviolet, visible, and infrared spectra, has been applied to monitor and optimize the cold storage process of peach and mango (Table 1). Although only a few studies have been carried out (Table 1) [77,78], this spectral approach can however give an accurate prediction (≈96%) of the total soluble solids, and phenolic content of peaches during cold storage. This technique gives the advantage of repeatable spectral data and provides high resolution of spectra. Additionally, this method is toxic-free. Nevertheless, the spectra data often contains redundant information due to hundreds of spectral variables, limited sensitivity to minor components, and complicated analysis.

X-ray imaging was applied to detect both the internal disorder and external changes (firmness) of pears and kiwifruit during cold storage, respectively (Table 1) [11,79]. This technology involves the production of electromagnetic radiation by an X-ray tube when passed through a product to absorb part of X-ray beam energy [80]. Using SVM, FEA, NN, and LDA, X-ray adequately quantified the columella firmness of kiwifruit and discriminated healthy pear from defective ones, with accuracy ranging from 90% to 95% (Table 1).

Other techniques used to monitor the quality of fruits and vegetables in postharvest cold chains are multi-sensors, electronic nose (E-nose), acoustic impulse response, radio frequency identification (RFID), and printed sensors (PTS). In this study, multi-sensors involves the use of numerous sensors placed at different locations on the produce and in the cold chain equipment (storage container or transport vehicle) to capture important quality attributes (e.g., color, firmness) and food losses (weight loss, temperature, time) metrics [81]. Data from the sensors are processed using sensor fusion (soft sensors). Soft sensors are virtual software code to process multiple sensor information for identified quality classifiers and for the development of warning systems (e.g., quality decline in fruits) [82]. They can be developed using different methods including mechanistic modeling based on physics of specific measured quality and food loss metrics, statistical modeling based on low-level representations in the feature space, and chemometrics or deep learning-based sparse representation techniques for multi-modal event modeling. Figure 3 depicts the use of multiple sensors (e.g., temperature, humidity) coupled with imaging technology during the cold storage of fruits and vegetables. From Table 1, only two studies applied multi-sensors to improve the accuracy of continuous sensor data acquisition in order to enhance transparency and traceability of the cold storage and transportation logistics of pear [83,84]. The multi-sensors monitored critical parameters that affect the quality attributes of fresh produce, including temperature and relative humidity (using portable low-energy-demanding temperature and humidity sensors). The detection of these parameters during shipment allows for effective control of safety and quality changes of the pear. Similarly, a study was reported on the use of an electronic nose (an instrument used to detect volatile organic compounds) [85] and acoustic impulse response to evaluate the quality of tomato and apple during cold storage, respectively (Table 1). The accuracy of the measured quality attribute (firmness) and mass loss data using ANN was ≈85%. This value is lower than those obtained using the aforementioned imaging technologies. This could be because of the complex nature of the method, which is based on the measurement of the sound emitted by fruit as it vibrates in response to a gentle tap with a small pendulum [86].

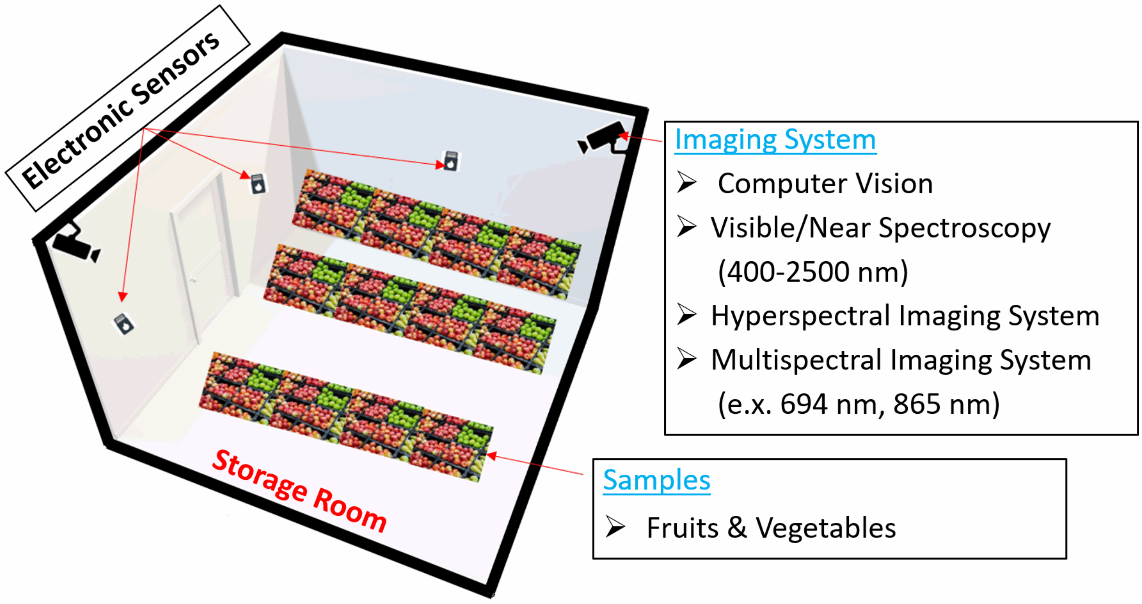

Figure 3. Schematics of multi-sensors coupled with imaging system for monitoring the quality of fruits and vegetables during cold storage.

RFID has also been applied as an advanced tool for identifying internal and external changes in the physical, biochemical, and physiological processes of packaged food [87–89]. This non-contact identification communication technology can automatically identify multiple objects moving at high-speed, and therefore can be applied in the transport cold chain, specifically as an IoT enabler [90]. Similarly, PTS which uses the printing process, such as inkjet printing, nanoimprinting, screen printing, etc., to prepare electronic circuits on a flexible substrate enables the monitoring of temperature, moisture, pressure, and motion of fresh produce [91]. This technology has the advantage of flexibility when printed on substrates, ease of distribution, and low cost especially when compared to RFID [91]. However, their application as tools in monitoring and optimizing cold chain processes is scarce.

Furthermore, there is no study on the application of imaging technology and smart digital technologies to monitor food quality losses during the transportation of fruits and vegetables. This is surprising considering that food losses in the transportation stage of the food supply chain can be as high as 30% as in the case of Poland, for example [92]. For this reason, future studies on the application of imaging technology, spectroscopy, multi-sensors, electronic nose, acoustic impulse response, RFID, PTS in the postharvest cold chain of fruits and vegetables should focus on the transportation chain.

Table 1. Published articles on the application of imaging technology, spectroscopy, multi-sensors, E-nose, and acoustic impulse response in assessing the quality of fruits and vegetables in the postharvest cold supply chains.

S/N	Technology	Cold Chain Operation	Purpose	Food Type	Statistical Approach	Significant Results	Reference
1.	Imaging technology hyperspectral Imaging	Packaging and storage	To study the image characteristics of vegetables acquired during packaging and storage	Spinach	SG, SNV, PCA	The arterial images were able to sense the aging of the leaves	[72]
2.	Imaging technology hyperspectral Imaging	Packaging	To study the refrigeration conditions of vegetables during packaging	Mushrooms	PLS, PLSR, MSC, PLS-DA	This method suggested an effective packaging solution to extend shelf life and prevent food losses of mushrooms during storage.	[73]
3.	Imaging technology multispectral imaging technology	Storage	To monitor and evaluate agro-food spoilage during storage	-	PLS-D	The spoiled food was predicted with an overall classification rate of 91.8%	[76]
4.	Imaging technology hyperspectral image	Storage	To explore the potential for the detection of chilling induced damage in fruits and vegetables	Cucumber	PCA	An overall classification rate of 90%	[74]
5.	Imaging technology computer vision system	Storage	To evaluate the effect of hydration degree during storage	Strawberry	PCA	Lighter appearance up to 75%	[58]
6.	Imaging technology machine vision systems	Storage	To monitor the quality change of food during storage	Orange	ANN, CART, CNN, LDA, kNN	An overall classification rate of 91.5%	[59]
7.	Imaging technology NIR hyperspectral image	Storage	To study the mechanical damage in fruits	Mango	CFS, GIA, SFS, SLR, LDA, kNN	Accuracy of 97.9%	[75]
8.	Imaging technology X-ray CT	Storage	To preserve the quality of fresh fruit during the supply chain and long-term storage	Pear	SVM, FEA	The X-ray computed tomography successfully detected the internal disorder severity of pear fruit with classification accuracies ranging between 90% and 95%	[79]
9.	Imaging technology computer vision	Storage	To develop a shelf life prediction model for postharvest handling of fruits and vegetables	Grape	RBF, NN	The method found the prediction accuracy of R^2 0.91	[60]
10.	Imaging technology computer vision	Storage	To study changes in color features of fruits during storage and to evaluate the use of image analysis technique as a rapid and nondestructive method	Banana	RBF, SVR, ANN	The computer vision technology with SVR of color parameters provided a useful model for prediction of the quality indices of bananas	[61]
11.	Imaging technology computer vision	Storage	To provide an application designed for embedded devices such as mobile Android smartphones to objectivize the measurements using machine vision	Tomato and zucchini	HA	The proposed method successfully achieved by predicting the quality characteristics of the products during cold storage	[62]
12.	Imaging technology computer vision system	Storage	To develop a computer vision system to predict the quality levels of vegetables during storage	Lettuce	SNK	The color information measured by the computer vision system achieved nondestructively to evaluate the quality level of iceberg lettuce with R^2 of 0.77	[63]
13	Imaging technology computer vision	Storage	To demonstrate the applicability of Random Forests (RF) for estimating the internal qualities of fruits based on peel color	Mango	RF	The relationship between peel color and fruit quality was strongly found in different storage temperatures with a correlation coefficient up to 0.98	[64]
14.	Imaging technology X-ray	Storage	To design a methodology for sorting fruits with X-ray image processing and pattern recognition techniques	Kiwifruits	NN, LDA	The model built with LDA predicted the columella firmness in kiwifruit with a 94.6%	[11]
15.	Imaging technology thermography	Packaging	To study the temperature distribution on a pallet of fruits during plastic boxes and cardboard packaging	Apples	ANN	Thermal imaging showed the cardboard boxes to be a better packaging material for apples compared to plastic boxes	[93]

Table 1. *Cont.*

S/N	Technology	Cold Chain Operation	Purpose	Food Type	Statistical Approach	Significant Results	Reference
16.	Imaging technology hyperspectral imaging systems	Storage	To develop a feature selection technique in classifying problems for detecting rottenness in tropical fruits	Citrus fruits	ROC, NN	Hyperspectral images found the classification success rate of around 89% for detecting the rottenness in citrus fruits	[75]
17.	Imaging technology multispectral Imaging	Storage	To evaluate chilling injury in fruits during storage using multispectral imaging	Mangoes	LS-SVM, PCA	The statistical results demonstrated significant changes in the reference quality properties of samples before and after storage	[70]
18.	Imaging technology computer vision systems	Packaging	To evaluate the quality of vegetables nondestructively using computer vision during packaging	Iceberg lettuce	CNN	The CNNs method was able to identify the lettuce quality with an accuracy of 86%	[65]
19.	Imaging technology computer vision systems	Storage	To evaluate fruit quality nondestructively by computer vision	Grapes	RF	The system achieved a cross-validation classification accuracy up to 92% which support its capability of powerfully, flexibly, and continuously monitoring the quality of the complete production along the whole supply chain	[66]
20.	Visible/shortwave near-infrared spectroscopy	Storage	To establish optimal spectral models for the assessment of fruits in actual production and therefore obtain early warning information of mechanical injuries during storage	Peach	GA	The optimal spectral model through the GA-PLS method found prediction accuracy ranges from 0.89 to 0.91 of the mechanical injuries of peaches during storage	[77]
21.	Handheld spectroscopy	Storage	To develop a nondestructive assessment of fruit quality using handheld micro NIR spectroscopic device	Mango	SVM, PLS	The proposed method was able to detect the mango fruit quality during the storage with prediction accuracy up to 96%	[78]
22.	Multi-sensor technology	Transportation and storage	To provide decision support to quality change and control	Pear	BPNN	The results indicated that this method could improve the accuracy of continuous sensor data acquisition	[83]
23.	Multi-sensor technology	Storage	To monitor and improve the data accuracy of sensory and physiological quality attributes of fruits during cold storage	Korla fragrant pear	BPNN	The multi-sensors technology including temperature, relative humidity, O_2, CO_2, and ethylene sensors improved the accuracy of data acquisition for gas content, pH, firmness, and total soluble solids	[84]
24.	Electronic nose	Storage	To investigate the reliability and validity of using the electronic nose to evaluate the quality and freshness of vegetables after high-pressure argon treatments	Cherry tomatoes	ELM, PLS	The results demonstrated E-nose technology combined with ELM provided a reliable and valid method for evaluating the quality and freshness of cherry tomatoes during cold storage with fitting correlation coefficients ($R^2 > 0.95$)	[85]
25.	Acoustic impulse response	Storage	To apply for apple classification nondestructively	Apple	ANN	The accuracy was 84.9% and 84.7% for Golden Delicious and Red Delicious, respectively	[86]

3.2. Application of Mathematical Modeling Techniques in the Postharvest Supply Chain of Fruits and Vegetables

Modeling is the act of representing phenomena or processes in such a way as to explicitly describe an observed system and to predict or optimize different behaviors, parameters, and conditions [94]. Mathematical modeling is essential for efficient engineering design and optimization. With adequate mathematical models, undesirable effects that significantly causes food losses such as weight loss, or quality changes can be predicted, thus cold chain logistics can be optimized or controlled.

Mathematical modeling techniques are becoming increasingly popular as an alternative to expensive and difficult experiments of postharvest cold chain operations as a result of the sophistication and reliability of computers as well as the affordability and availability of modeling software [95–99]. Agricultural and food engineers, and other researchers have over the years developed different mathematical models for postharvest supply chains. Depending on the complexity, these different modeling techniques have been developed to predict heat and mass transfer, fluid flow, and quality changes in and around fresh produce. Gas exchange and in-depth understanding of migration from packaging material to fresh produce have been described using mathematical models. Additionally, several deterministic, stochastic and kinetic models have also been developed to predict the overall quality of fresh produce, mass loss, fluid flow, and heat and mass transfer during the transportation and storage of fruits and vegetables [98,100–106].

In this study, mathematical models used to enhance cold chain operations chain can be separated into six different types based on their specific process application, namely: migration models (MM), membrane gas separation (MGS) model, heat and mass transfer (HMT) model, structural behavior models (SBM), stochastic models (SM), and kinetics rate models (KRM) (Table 2). MM are often used to study the migration of organic compounds such as Benzophenone, Diisobutyl phthalate, and Phenanthrene from packaging material to fresh produce. On the other hand, MGS models are often used in a modified atmosphere (e.g., modified atmosphere storage or modified atmosphere packaging) to study the lifespan of fresh produce by reducing the respiration rate through the adequate regulation of atmospheric conditions (e.g., CO_2, O_2). Additionally, to abstract the packaging of different fruits and vegetables [107]. This type of model works on four ideal flow patterns for a mixed gas module including co-current flow, cross flow, counter-current flow, and perfect mixing [108–110].

HMT modeling also called hygrothermal modeling involves using a numerical physics-based method such as computational fluid dynamic (CFD) to solve the governing partial differential equations of heat and mass transport phenomena in a system, often using finite element analysis (FEA) [100,105,111,112]. HMT models describe the underlining physics inside fresh produce and how they are affected by the surrounding conditions (Figure 4). They generally are independent of experimental calibration and validation. HMT models can also be used to investigate the impact of different packaging designs on the convective heat transfer rate of fruits and the surrounding [105]. By reducing heat transfer from the outside environment, effective packaging can help to shield the product from temperature variation in the storage and transport process. In addition, increasing the packaging heat transfer resistance can also ensure temperature stability of the fresh agricultural produce [113,114]. There is therefore a need for simulation tools and numerical models that analyze all factors affecting optimum packaging design.

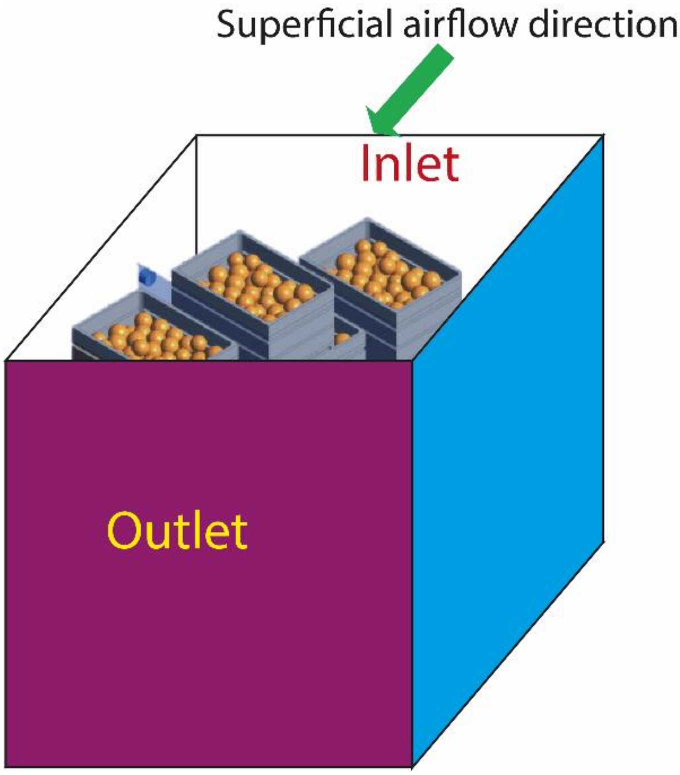

Figure 4. Simulation domain showing loaded fruits in stacked cartons in a virtual wind tunnel system with internal and external surrounding conditions [101].

SBM involves the study of structural and mechanical properties of packaging materials for fresh produce using FEA (Table 2). This modeling approach encompasses a geometric representation, material representation, and boundary conditions (loading and restraints).

SM involves predicting the variability of certain generated data following their probability distribution, and then evaluating of results statistics until the minimum error becomes constant [115]. These models are often used to analyze the effect of biological variability on food quality and losses during the supply chain, and also to quantify the efficiency of the cold chain technology [102,103,116]. Although they do not provide a fundamental understanding of the underlying physics, they are however very reliable and flexible.

KRM are temperature-dependent and are frequently used to study the combination of the rate of reaction with the material balance to predict the behavior of a particular system. Nutritional and sensory qualities of fresh agricultural produce in the postharvest supply chain can be quantified based on kinetics, such as zero-order, first-order, second-order, mixed order, or higher-order reactions [117].

From Table 2, most modeling studies were conducted on packaging followed by storage with very little modeling studies on the transportation of fruits and vegetables. Over 25 modeling studies on the packaging of fruits and vegetables during the postharvest cold chain were conducted within the last decade (Table 2). The products studied were apple, tomato, carrots, strawberries, capsicum, citrus, avocado, grape, feijoa fruits, and pears [100,101,105,107,112,116,118–137]. The bulk of the studies used HMT models to describe the cooling process in a packaged material during storage [100,101,104,105,112,119,120,130,131,137–140]. Seven studies applied MGS models to modify the atmospheric conditions of fresh agricultural produce in packaging material (Table 2) [118,121,125–127,135]. While, four studies examined the migration of chemical compounds (e.g., Benzophenone, Diisobutyl phthalate, and Phenanthrene) from packaging material to fresh produce using MM (Table 2) [122,124,134,136]. Several researchers also reported the application of KRM, SBM, and SM during the packaging of fruits and vegetables (Table 2) [116,123,128,129,132,141].

Table 2. Summary of recent literature on the application of mathematical modeling in monitoring quality loss of fruits and vegetables in postharvest supply chain fruits and vegetables.

S/N	Technology	Cold Chain Operation	Purpose	Food Type	Significant Results	Reference
1.	Membrane gas separation modeling	Packaging	To predict changes in fresh produce on molecular level based on changes in environmental conditions; to reduce losses	Apple	A membrane-based model can be used to abstract packaging for different fruit and vegetables; respiration of the process is considered important in modeling, and also environmental biological and technical factors; quality (taste, texture, color, appearance) is based on some subjective consumer evaluation	[107]
2.	Migration modeling	Packaging—paper and board	Deepened understanding of migrants from paper and board into foodstuffs	Tomato	Migration rate from paper and board to food at low temperatures is small compared to plastic material. For modeling, paper and board can be regarded as a two-layer system	[134]
3.	Membrane gas separation modeling	Packaging	To study the effect of external turbulence on the gas exchange rate; to develop a mathematical model to predict the effect of tube dimensions	Carrots	Different hydrodynamic condition affects the gas exchange rate in PM-MAP (perforation-mediated modified atmosphere packaging); the effect of temp, air velocity, and tube diameter on O_2 and CO_2	[135]
4.	Kinetic modeling	Storage	To predict the remaining shelf-life after storage; to predict dipp loss (zero-order), vitamin C (first-order), color (zero and first order) food quality	Broccoli	The model only looked at temperature effect on shelf life and adequately predicted the shelf life based on a 50% threshold of vitamin C loss at −18°C	[144]
5.	Migration modeling	Packaging migration controlled by diffusion	To use the Weibull distribution model to quantify migration in food packaging systems	-	Migration depends on the type of contact, food stimulant, type of paper, chemical nature of migrant in a paper, temperature and time of contact; migration is faster in paper than in plastics and involves the simultaneous transfer into food and also to the atmosphere	[136]
6.	Heat and mass transfer modeling	Packaging; storage	To quantify the impact of ventilation vent on temperature distribution of product	-	Decreasing the number of vents increased the cooling uniformity; the model, based on velocity and temperature simulation can be used as a design tool to provide homogenous temperature distribution to reduce food losses	[112]
7.	Heat and mass transfer modeling	Packaging	To predict O_2, CO_2, N_2, and H_2O concentrate in perforation-mediated polymeric packages; transport of O_2, CO_2, N_2, and H_2O was modeled using Maxwell Stefan equation for gas and Fick's law for diffusion through the micro-perforated package	Strawberries	The model result suggests an improvement in material properties, especially with regard to the permeability of polymeric packaging film; the model predicted a packaging with 30 μm thickness, 6 micro-perforation of 50 μm diameter each as the most suitable	[137]
8.	Heat and mass transfer modeling—based on compartments	Transport; storage	To predict temperature distribution during transport and storage of fruits and vegetables	Spinach, apricots, and peaches	The model adequately predicted the maximum and minimal load temperature distribution with lower computational time compared to CFD simulation	[104]
9.	Membrane gas separation modeling (Michaelis–Menten kinetic model + mass transfer model)	Packaging; storage	To describe the evolution of MAP of capsicum using a mathematical model; to quantify the performance of different packaging under the dynamic condition of use	Capsicums	Temperature and perforation have a significant effect on MAP conditions of capsicum; the combined model adequately predicted O_2 and CO_2 under different storage conditions	[118]
10.	Heat and mass transfer modeling	Packaging; storage	To assess the sensitivity of produce cooling uniformity and cooling time with respect to the packaging vent design	-	Increase in the number of vents increased cooling uniformity and reduce cooling time	[119]
11	Stochastic modeling (Monte Carlo simulations) + kinetic modeling	Storage; transportation	To estimate the expected fraction of perished products	Peaches	The simulation study predicted a fraction of 8.00% perished products based on a 100.00% quality threshold. The model quantifies thereof.	[143]
12.	Heat and mass transfer modeling	Packaging	To develop a 3D heat and mass transfer model of a fresh food produce packaging system to predict airflow and heat transfer characteristics	Citrus	Airflow, temperature, and turbulence property distribution inside a single product are nonuniform; good correlation between air velocity and temperature; the accuracy of the model depends on geometry, thermal, physical, and chemical properties of the package, the cooling air, and the produce	[120]
13.	Membrane gas separation modeling	Packaging; storage; transportation	To develop a mathematical model to investigate the effect of stage cut on the gas separation performance of hollow fiber membrane modules	Avocado	The model utilizes pure gas permeances of membrane material to predict the mixed gas separation performance; the performance of gas separation declines over time as they age with exposure to pressure, temperature, and contaminant loading	[121]

Table 2. *Cont.*

S/N	Technology	Cold Chain Operation	Purpose	Food Type	Significant Results	Reference
14.	Kinetic modeling	Storage	To evaluate the impact of storage conditions on vegetable color, firmness, weight loss, and phenolic content; to investigate the kinetics of quality parameters alterations of stored vegetables	Tomato	Fractional kinetic model fitted adequately well with experimental data; Arrhenius model describes well the temperature effect on all factors studied	[142]
15.	Migration modeling	Packaging; storage	To study the influence of box material and plastic cover on the distribution of 1-MCP (methyl cyclopropane) in cold storage to delay ripening of fruit	Apple	Diffusion, convection, and adsorption were modeled to simulate the temporal distributions of 1-MCP inside a storage container, boxes, and fruits; the plastic cover does not affect the adsorption of 1-MCP; wooden boxes notably adsorbed 1-MCP from the treatment atmosphere and may reduce the efficacy	[122]
16.	Kinetic modeling	Packaging	To investigate the impact of temperature and relative humidity on fruit transpiration rate (TR); to develop a prediction model for quantifying TR; to integrate TR model into engineering packaging design and quantify	Strawberries	Temperature and relative humidity have a significant impact on the transpiration rate of strawberries; increase in relative humidity increases TR; decreasing temperature decreases TR; the model predicted the water vapor barrier properties required for maintaining optimal relative humidity inside package	[123]
17.	Heat and mass transfer modeling	Storage	To model the airflow and temperature distribution in a natural connection thermal energy storage refrigerator; to determine the performance of the refrigerator with different phase change material (PCM) vertical-horizontal	-	Horizontal PCM configuration produces lower compartment temperatures than a vertical configuration; combining horizontal and vertical configuration gives better design performance	[140]
18.	Migration modeling	Packaging; storage	To study the diffusion, convection and adsorption of 1-MCP gas in cold stores; to understand the mechanism of 3D distribution of 1-MCP	Apple	The model demonstrated the absence of significant spatial variation of 1-MCP gas in a container; diffusion–convection in air and diffusion–adsorption in the product	[124]
19.	Heat and mass transfer modeling	Packaging	To develop a porous medium model was develop on volume averaging of transport equations of momentum and 1-MCP in air and product	Apple	The velocity field in and around the stack was well reproduced by the porous medium model; the porosity, skin mass transfer coefficient, and specific surface area strongly affected the simulation process	[100]
20.	Heat and mass transfer modeling	Packaging (bunch carry bag and plastic liners)	To determine the effect of the packaging component and box stacking on airflow, heat, and mass transfer rate	Grape	The use of carry bag resulted in an increase in the cooling time; the addition of plastic liner over the bunch carry bag increased cooling time; moisture loss was most prevented using nonperforated liners; CFD simulation determined optimum table grape packaging and costing procedure	[101]
21.	Heat and mass transfer modeling	Storage; packaging	To evaluate the performance of corrugated fiberboard, Supervent, Ecopack re-usable plastic container; to check the influence of airflow rate and cooling	Citrus	With respect to cooling, Eco-pack showed lower convective heat transfer rate but cooled in a uniform way, which improves fruit quality	[105]
22.	Membrane gas separation modeling	Packaging	To predict the shelf life of MAP systems	-	The model was able to predict the mass transfer phenomena for O_2 and CO_2 and also the microbial growth in the food system	[125]
23.	Kinetic model	Storage	To describe the product time–temperature history along the cold chain; the model considered front and rear air circulation in the cold room	Apples	The model adequately predicted cooling rate, the temperature at different positions, and weight loss; the model has a short CPU computational time (<1 s) when compared to CFD models. This enabled a rapid evaluation of input parameters such as air temperature	[106]
24.	Stochastic modeling	Storage	To evaluate the quality of perishable foods using a generic algorithm + center of gravity model; to estimate the environmental level	Fruits	The algorithm adequately predicted temperature and humidity levels; the algorithm was integrated to gauge the use of RFID (radio frequency identification) and sensors for real-time information gathering	[102]
25.	Stochastic modeling	Transport; storage	To estimate the heat generation and also the cooling efficiency during cold transport and storage chain	Banana	10% accuracy for the heat of respiration and cooling efficiency was reached after 4–7.5 days of transport	[103]
26.	Membrane gas separation modeling	Packaging; storage	To describe product respiration and gas exchange through package using Michaelis–Menten kinetics + Fick's equation; taking into account diffusive gas permeation through packaging film and perforation respiration rate and storage temperature	Tomato	The model adequately predicted the required package surface area and perforation diameter to achieve a specific O_2 concentration in the headspace; the model can be used to set a specific equilibrium concentration of O_2 and CO_2 by modifying the configuration of the package	[126]

Table 2. *Cont.*

S/N	Technology	Cold Chain Operation	Purpose	Food Type	Significant Results	Reference
27.	Membrane gas separation modeling	Packaging	To develop describe the evolution of water vapor, O_2, and CO_2 in packaging headspace, weight loss, and condensation of water in a MAP system	Feijoa fruits	The model adequately predicted weight loss and relative humidity in the MAP system	[127]
28.	Structural behavior modeling	Packaging	To develop a validated structural behavior model to predict the compression strength of a ventilated paperboard carton	-	The model adequately predicted the compression strength of a ventilated corrugated paperboard (VCP) packaging; the effect of vent area, vent height, and buckling load on the performance of VCP were adequately quantified by the model	[128]
29.	Heat and mass transfer modeling	Storage	To model the airflow, heat, and mass transfer in the storage chamber of Chinese cabbage; to predict the velocity, temperature, and relative humidity distribution	Cabbage	The model gave qualitative insight into the flow patterns in the cold room; the model adequately predicted temperature in the bulk and relative humidity of the air	[139]
30.	Stochastic modeling	Packaging; storage	To model the gas exchange in pear fruit taking the effect of biological variability	Pears	The model predicted that O_2 and CO_2 gas profiles inside the fruit were highly impacted by diffusivity, maximal respiration rate, and morphology of fruit; the model was used to analyze the incidence of fermentation at reduced O_2 levels during controlled atmosphere storage	[116]
31.	Structural behavior modeling	Packaging	To simulate the compression of paper and paperboard packaging material for food using finite element analysis (FEA)	-	The developed FEA model accurately predicted the incident buckling load of the corrugated paperboard; the modulus of elasticity was observed to be sensitive to the environmental conditions; the model can adequately be used to optimize corrugated paperboard packages	[129]
32.	Heat and mass transfer modeling	Packaging	To develop a more accurate model for describing the cooling process of freshly harvested apples and pears	Apples; pears	The model was able to describe the cooling behavior and uniformity of fruits in fiberboard boxes; there was large variability in convective heat transfer coefficients from the apples and pear filling; the fruit shape affects the model accuracy	[130]
33.	Heat and mass transfer modeling	Packaging	To develop a 3D HMT model to quantify cooling behavior of 10 different carton designs based on cooling rate, energy consumption, uniformity, weight loss, and chilling injury of apples	Apples	The model adequately quantified the effect of airflow, and packaging design on the product quality; vent area, shape and number of vent have less impact on the fruit cooling; homogeneity and symmetry of packaging vent positions have more impact on the fruit cooling rate; the model proposed airflow velocity between 0.4 and 1.0 m/s	[131]
34.	Structural behavior modeling	Packaging	To develop a validated structural behavior model to study the structural behavior of VCP packages by considering the geometrical nonlinearities of the packages	Fruits and vegetables	The model accurately predicted the compression strength of the corrugated paperboard, control package, and standard vent package; compression strength of the standard vent packages was found to be linearly affected by paperboard liner thickness; increasing and decreasing the baseline liner thickness of the standard vent package by 80% resulted in an increase and decrease in compression strength by about 15% and 19%, respectively; from the contact FEA model, maximum Von Mises stress was produced at the corners of the package; Von Mises stress was significantly affected by the coefficient of friction	[132]
35.	Heat and mass transfer modeling	Storage; transport	To investigate the airflow distribution inside two types of refrigerated shipping containers (T-bar floor and flat floor) used for transporting fresh fruit handling		The airflow distribution in the two container designs was markedly different. Good agreement was found between measured and predicted values of air velocities. The reefer with T-bar floor design exhibited a noticeable reduction of air recirculation zone and enhanced uniform vertical air movement compared to the reefer with flat floor design	[138]

Table 2. *Cont.*

S/N	Technology	Cold Chain Operation	Purpose	Food Type	Significant Results	Reference
36.	Kinetic modeling	Storage	To examine the effect of relative humidity (RH) conditions on the shelf life of strawberries including both the sensory and nutritional quality; to study the kinetics of sensory and chemical changes occurring in strawberries during storage by comparing three kinetic models; to examine and predict through modeling the waste that would occur depending on the storage conditions	Strawberries	Weight loss significantly increased when storage RH decreased; the weight loss was correlated with the changes that occurred in visual appearance and chemical properties. Overall appearance (i.e., the average score of color and shriveling), was modeled with a zero-order kinetics model for the various RH conditions; lower RH increased the rate of appearance deterioration thereby reducing the remaining shelf life of strawberries. The Weibull model adequately fitted the chemical properties data and it was found to be an important tool in describing the changes that occur with varying storage conditions	[98]
37.	Stochastic modeling	Whole chain	To develop an Agro-Chain Greenhouse gas emissions calculator (ACGE calculator) to calculate the percentage of food losses per chain stage	Cut vegetables	The ACGE calculator can be applied for understanding the impacts of different operations along a postharvest cold chain and for analyzing chain configuration scenarios: such as weighing impacts of the operations/impacts along the chain, comparison between various options for supplying a specific food component, and comparing a reference scenario with an 'improved scenario'; low temperature in the cold chain may result in extended retail shelf life and a lower percentage of losses, but will cost more energy; application of protective packaging leads to a reduction of losses, but at the cost of the packaging	[141]
38.	Heat and mass transfer modeling	Transportation; storage; packaging	To obtain more insight into the cooling process and quality evolution of fruits parked in ventilated cartons in a pallet	Citrus	Fruits packed in downstream cartons exhibited lower cooling heterogeneity compared with those in upstream cartons. Precooling reduced quality loss by 23%	[133]

With respect to storage, several researchers developed various models to predict quality loss during the storage of carrots, strawberries, spinach, apricots, peaches, capsicums, banana, cabbage, pears, citrus, and broccoli, however not all together (Table 2) [98,102–106,116,118,119,121,122,124,126,133,138–140,142–144]. A bulk of the models used were based on heat and mass transfer simulations of the weight loss, and temperature distribution; KRM for quality decay and shelf-life prediction (Table 2) [98,104–106,112,119,133,138–140,142,144].

Concerning the transportation supply chain, only a few authors have applied SM, HMT models, and KRM to estimate heat generation, cooling efficiency, temperature distribution, and the expected fraction of perishable products (Table 2). These products include spinach, peaches, and banana [103,104,143].

The above analysis shows that mathematical models have been widely developed and applied in the packaging and storage of fruits and vegetables with the view to improve quality and reduce food losses. However, not so much modeling study for the transportation supply chain of fruits and vegetables. Future mathematical modeling studies should focus on the transportation supply chain taking into account the shipment time, the varying environmental conditions (e.g., temperature, humidity, and airflow), packaging, and vehicular movement. In addition, the KRM could be integrated with HMT models to give more insight into what extent the quality attributes of fruits and vegetables are preserved better and also to quantify the effect of other drivers for decay processes (e.g., relative humidity, light) in the fresh produce supply chain. This can be achieved by developing a digital twin of the product (see Section 4.2).

4. Emerging Opportunities in Reducing Food Losses in the Postharvest Supply Chain

The application of IoT and digital twins in optimizing shelf-life and reducing food losses during an entire shipment has gained significant interest in recent years. This section analyzes the potential of applying the Internet of Things (IoT) and digital twins in reducing food losses in the postharvest supply chains of fruits and vegetables.

4.1. Application of IoT in the Postharvest Supply Chain of Fruits and Vegetables

IoT has emerged in different fields such as e-commerce [145,146], manufacturing [147,148], education [149–151], medicine and healthcare [152–158], and agriculture [159,160]. This is because of the enormous number of devices connected to the Internet, as well as the widely available internet and data storage service providers [148,161,162]. Basically, IoT allows humans, objects, and things to connect and communicate at any time and anywhere. The European Commission Information Society defined IoT as different things exhibiting identical and virtual personalities, connecting and communicating in a smart space using intelligent interfaces within social, economical, and user contexts [163].

The IoT system consists of networks of physical objects that contain embedded technology to sense, communicate, and interact with their internal states or the external environment [164]. The key enablers for a typical IoT system include RFID, printed sensors, web service, machine-to-machine communication (M2M), WSN, imaging system, multi-sensors, cloud, blockchain, among others, but not necessarily altogether [87,91,147,161,165,166].

The application of IoT is well-established in various agricultural production sectors such as controlled environment agriculture, open-field agriculture, and livestock applications [167,168]. In recent years, the use of IoT has gained significant interest in the food industry for product tracking, traceability and the monitoring of environmental conditions (e.g., temperature, humidity), weight loss, and the overall quality loss in the postharvest supply chain [87,161,165,169–171]. This technology has also received significant attention in developing intelligent packaging in the food sector [172–174].

Intelligent packaging involves the use of sensors (biosensor, printed, chemical, and gas sensor) and indicators (time-temperature indicators, freshness indicators, gas indicators, and integrity indicators) to detect biological, chemical, or gaseous changes from packaged fresh produce [24,25,27,91,170,174–176]. The sensor-based RFID tags as an example can detect hygrothermal and chemical changes (e.g., temperature, CO_2, light exposure, pH, etc.) of the fresh produce in the post-harvest supply chain [25,87,175]. The timely information obtained within the package system can be used to inform stakeholders in the supply chain of an event that may damage the packaging material or the fresh produce itself.

Generally, the application of IoT in different cold chain processes results in a large amount of real-time data which can pave the way for new computational approaches such as artificial intelligence and big data analytics [161,177]. This data will help various stakeholders in the supply chain control and optimize the cold chain technology to reduce quality loss and also make informed decisions regarding food safety. However, the application of IoT in controlling cold chain technologies in order to reduce food losses in the supply chain of fruits and vegetables is still inadequate.

Table 3 shows that several studies applied IoT in tracking and tracing temperature changes and food quality during the shipment of fruits and vegetables in the past decade [20,159,165,178,179]. Two studies applied IoT on the packaging of fruits and vegetables, as well as during cold storage [159,178]. The application of IoT in the shipment of fruits and vegetables is accompanied by multi-sensors such as temperature and humidity sensors, light exposure sensors, and global positioning system (GPS) sensors (Figure 5) during shipment of fruits and vegetables (Table 3). These sensors are installed in the food containers to monitor the changes in the environmental cold chain conditions such as air temperature, airspeed, light exposure, and relative humidity using a sensor data fusion (soft sensors). They are connected to a wireless network and computers to communicate with control stations, producers, or other stakeholders in the supply chain. The collected data can then serve as input data in analyzing the changes in the food attributes (e.g., weight loss, shelf life, nutritional, or sensory qualities), using a mechanistic physics-based model or a digital twin. It is worth mentioning that multi-sensors (e.g., chemical sensors, biosensors, etc.), imaging systems (see Section 3.1), E-nose (see Section 3.1), spectroscopy (see Section 3.1), and AIR (see Section 3.1) can also be used to directly measure changes in some quality attributes of fresh produce in the postharvest supply chain. IoT has become a very important tool in monitoring and controlling the process conditions of food, allowing the controllers to implement proper decisions. All of these can help to significantly reduce food losses. More so, the reduced cost of software and hardware wireless devices [180], digital sensors, accompanied by IoT technology in food transportation, packaging, and/or storage already increases the potential of IoT as a veritable and sustainable tool for reducing food losses.

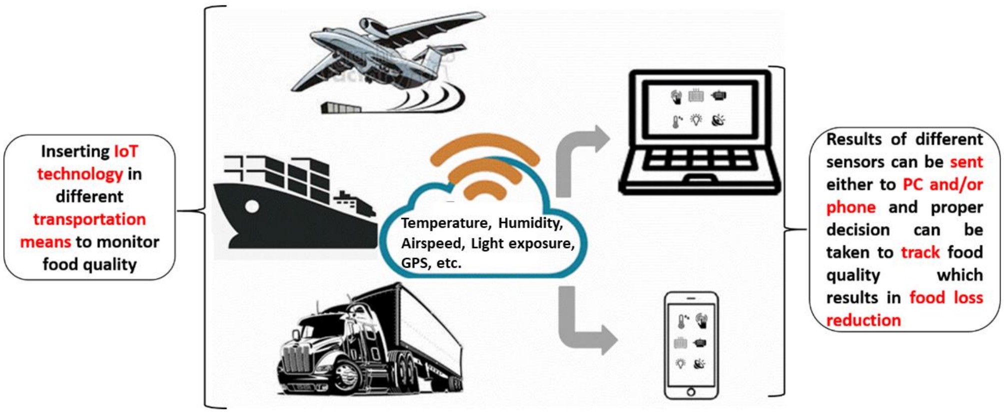

Figure 5. The implementation of Internet of Things (IoT) during shipment of fresh fruits and vegetables.

4.2. Digital Twin as an Advanced Tool in Reducing Food Losses in the Postharvest Supply Chain of Fruits and Vegetables

Digital twins have recently gained significant interest in postharvest engineering, as a way of expanding mathematical models and computer simulations by linking input data to the solutions implemented after the simulation study [181]. Simply, a digital twin of a product can be defined as a virtual model of the product's real-life representation containing all realistic characteristics.

The virtual model contains all essential elements, including geometrical components and material properties, and accurately and realistically simulates all relevant physics and their kinetics throughout the product's life-cycle. Digital twins can be mechanistic (physics-based), statistical (empirical-based), and intelligent (e.g., machine learning, deep learning) in nature. However, only the physics-based mechanistic digital twins can adequately evaluate the processes that cause quality loss in fresh produce. This involves linking measured sensor data of the environmental conditions (e.g., the air temperature around the fruit), as input data to the currently still uncharted product's quality evolution of fresh produce (Figure 6), preferable in a real-time update, using a physics-based model. In this way, the digital replica reacts hygrothermally and biologically in the same way as its physical counterpart (a real fresh fruit or vegetable).

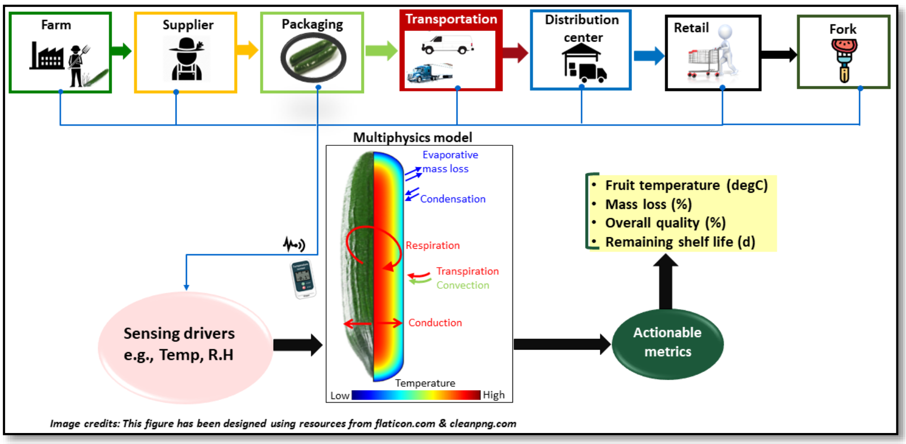

Figure 6. A schematic of a simple digital twin for fruit during the postharvest supply chain.

By enriching current real-time monitoring capabilities using sensors, digital twins can be used to diagnose and predict potential problems in the supply chain that will increase food losses. These problems can be caused by physiological (e.g., chilling injury), hygrothermal (e.g., mass loss), biotic (e.g., phytosanitary pests, pathogens), and mechanical (e.g., puncture injury, bruising) effects. This unique attribute shows that the digital twin has the potential of incorporating several physics-based thermal, physiological, mechanical, biological, and decay models for corresponding quality and shelf-life metrics. This insight can then help remotely analyze the quality performance of the fresh produce in each shipment and also predict the remaining shelf life days. Based on the analysis, a proactive preventive measure can be taken early to reduce quality losses throughout the cold chain. Such measures can also help predict and optimize future product quality and process design.

As a next step, digital twins can be implemented in real-time with actual multiple shipments. This is expedited with the integration of the already available big data technologies (e.g., IoT devices, blockchain devices, soft sensors, cloud systems, etc.) [182,183]. However, such a system is not yet in place, to the best of our knowledge (Table 3). From Table 3, only two studies developed a digital twin for mango. The mechanistic models developed for these studies included HMT models, as well as KMR for various quality attributes such as firmness, soluble solids content, and vitamin content [184] [185]. The air temperature data of the actual mango cold chain, collected as input from a temperature sensor was linked to these models to create a digital twin of a virtual mango fruit [184,185]. With the digital twins, the fruit quality evolution was quantified for multiple overseas shipments. However, the twin did not use other significant input data history such as the humidity of the products at the different supply chains. The temperature data collected was not in real-time, but offline, so a-posteriori. In addition, the digital twin did not integrate models to estimate the mass loss, chilling injury, and other biochemical models which are important for quantifying food losses in the entire cold chain (Table 2).

Table 3. Summary of recent literature on the application of IoT and digital twins in reducing food quality losses in the postharvest supply chain of fruits and vegetables in the last 10 years.

S/N	Technology	Cold Chain Operation	Purpose	Food Type	Significant Results	Reference
1.	Internet of Things	Transportation	To build an intelligent model for food quality monitoring and control in a multi-temperature distribution center	Food	The food spoilage rate of food reduced during transportation due to the real-time food quality monitoring and control using an intelligent model	[165]
2.	Internet of Things	Transportation	To improve transport efficiency in order to save the fruits from spoilage	Fruits	IoT system in a truck refrigerator adequately used to monitor the quality condition of fruits during transport	[20]
3.	Internet of Things	Packaging, storage, and transportation	To monitor food quality and safety	Fruits and vegetables	IoT obtain real-time food traceability and monitoring data to control the logistic and process parameters causing quality loss	[178]
4.	Internet of Things	Packaging, storage, and transportation	To reduce the food losses during the food chains since 50% is lost	Agro-food	IoT used to automate the packaging system with proper tracking and monitor the temperature of the produce at cold storage and during transportation	[159]
5.	Internet of Things	Transportation	To monitor the temperature changes and inefficient management during transportation as the insufficient temperature can pose a high risk to food quality	Fruit and vegetables	Application of IoT in food chains facilitated safety, intelligence, and deliver quick decisions	[179]
6.	Digital twin	Storage; transport	To develop a digital twin for the cold chain shipment of fruits	Mango	Based on measured environmental conditions, the impact of shipment duration, heat of respiration, airspeed and delivery air temperature history on quality of mango for different transport pathways was easily quantified using a digital twin	[184]
7.	Digital twin	All chain	To gain a better insight into how fruits behave under convective cooling	Mango	At low speeds, a more uniform cooling can be achieved and thereby a more homogeneous quality decay within the mango; digital twin was able to evaluate the heterogeneity of the temperature field and identified the zones with the highest temperature inside the product, which can be valuable information for the placement of temperature probes	[185]

5. Future Opportunities to Reduce Food Losses in the Postharvest Supply Chain of Fruits and Vegetables

With the gradual depletion of resources, there is a need to look at sustainable ways of achieving food security by reducing food losses in the postharvest supply chain. Looking ahead, the major challenges that cause food losses in the postharvest supply chain have to be addressed.

One emerging field is the development of intelligent packaging systems to reduce food losses, especially fresh agricultural produce. Intelligent packaging systems through the use of internal and external monitors (sensors, nanosensors, and indicators) provide valuable information on the interaction of food with the packaging material and the environment at different phases of processing, transportation, and storage. It also takes into consideration the ergonomic features of the packaging to reduce inconvenience in the transportation, storage, use, and eventual disposal of the packaging material [174,186]. With the recent interest and development in intelligent packaging, there is a need to integrate the sensors, indicators, and data carriers technologically to provide real-time information about fresh food in different cold chain logistics through the use of IoT based technologies and digital twin.

Although the potential of a digital twin in minimizing quality losses and increasing the shelf-life of fresh produce has been demonstrated (Table 3), the holistic implementation of digital twins in the entire value chain (from planting-fork) and for a wide range of fresh produce is yet to be demonstrated. The existing digital twins (Table 3) should be improved upon to include other relevant models that simulate thermal, physiological, mechanical, and biological damages that cause food losses in the postharvest supply chain. For example, a mass loss model can be included to quantify the salable weight at the end of the chain. This can help quantify the market value of fresh produce due to the subjective acceptable consumer product appearance. Additionally, tropical fruits such as banana or papaya experience chilling injury due to low-temperature storage and long cold chain process (Table 1). Therefore, thermal damage models predicting chilling injury during cold chain processes should be included. The potential of linking pathogens with decay severity should also be a future focus. Future digital twins should also capture the biological variability of fresh produce in order to give more realistic actionable metrics as multiple fresh produce have different individual pre-harvest and postharvest history. This can be achieved by integrating stochastic simulations (e.g., Monte Carlo simulations) with the existing digital twin physics-based models.

An additional future focus is to integrate IoT systems (including soft sensors) in real-time with digital twins. This real-time coupling will enable stakeholders to monitor and control each supply chain shipment at all times and take dynamically corrective measures to reduce quality loss and increase the remaining shelf-life days. Furthermore, by adding more "intelligence" to the coupled IoT and digital twins system, the cold chain technology (e.g., a refrigerated container) can independently optimize its process parameters to increase the shelf life of fresh produce and reduce food losses of the entire shipment. This added value can be easily quantified especially in this current time, considering the COVID-19 situation. Due to COVID-19, food producers have seen a decrease in the timely distribution of fresh produce to supply chain retailers. This is attributed to the decrease in transport labor, and longer shipment time because of shipment re-routing. This development has led to increased food losses. As a consequence, for example, about 5 billion US dollar worth of fresh fruits and vegetables were lost in the USA alone during the COVID-19 peak period from March 2020 to June 2020 [187]. With intelligent coupled IoT and digital twins, different processes and cold chain technology can be optimized to reduce the dependency on human labor, faster shipment duration, and possible damages caused by physiological, hygrothermal, mechanical, and biotic factors. A reduction in damages on the fresh produce implies a reduction in food losses.

6. Conclusions

Fruits and vegetables are important sources of nutrients such as vitamins, minerals, and bioactive compounds, which provide many health benefits. However, due to poor postharvest management processes, large quantities of fruits and vegetables perish before they reach the consumer. Of all the techniques for extending the shelf life of perishable produce, storage at low temperatures is by far the most effective.

This study, therefore, provides in-depth insight on the application of advanced technology in improving food security, by reducing food losses during postharvest cold chain processes for fruits and vegetables. It has been found that:

- Computer vision, hyperspectral imaging, multispectral imaging, spectroscopy, and X-ray imaging are already widely used in monitoring and optimizing the cold chain processes of fresh agricultural produce.
- The application of MM, MGS models, HMT models, SBM, SM, and KRM in improving the cold chain processes and evaluating the quality losses of fresh produce is well established. These models can help control and optimize the packaging and storage operations of fruits and vegetables in order to reduce quality losses.
- IoT is widely applied in monitoring and controlling the process conditions of fresh produce, enabling various stakeholders to implement proper decisions.
- Digital twins are significant in quantifying the quality evolution of fresh produce in each shipment and also predict the remaining shelf life days.
- There is a very huge potential for coupling digital twins with big data technologies (IoT devices, printed sensors, RFID, multi-sensors, soft sensors) to monitor, optimize, and make significant changes that will reduce food losses in the postharvest supply chain of fresh produce. However, such a system does not exist.

The augmented insight on the application of emerging technologies can serve as a roadmap for future cold chain studies on fresh agricultural produce.

Author Contributions: Conceptualization, D.I.O. and G.C.; methodology, D.I.O.; investigation, D.I.O., N.E.-e., A.K., A.Y.K., B.S.; data curation, D.I.O., N.E.-e., A.K., A.Y.K.; writing—original draft preparation, D.I.O.; writing—review and editing, D.I.O., N.E.-e., A.K., A.Y.K., G.C., B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

FAO	Food and Agriculture Organization
AIR	Acoustic Impulse Response
CV	Computer Vision
HSI	Hyperspectral Imaging
MSI	Multispectral Imaging
CCD	Charge-Couple Device
SG	Savitsky–Golay
SNV	Standard Normal Variate
PCA	Principal Component Analysis
PLSR	Partial Least Squares Regression
MSC	Multiple Scatter Correction
PLS-DA	Partial Least Squares Discriminant Analysis
ANN	Artificial Neural Network
CNN	Convolutional Neural Networks
LDA	Linear Discriminant Analysis
kNN	k-Nearest Neighbors
CFS	Correlation-based Feature Subset Selection
GIA	Gini Impurity Algorithm
SFS	Sequential Forward Selection
BPNN	Backpropagation Neural Network

ELM	Extreme Learning Machine
SLR	Sparse Logistic Regression
CMS	Central Monitoring System
RTS	Real-Time analytic System
RFID	Radio Frequency Identification Tags
MSA	Multi-Sensors Analysis
SVM	Support Vector Machine
RBF	Radial Basis Function
LCA	Life Cycle Assessment
PTS	Printed Sensors
GA	Genetic Algorithm
SVR	Support Vector Regression
SNK	Student–Newman–Keuls
LS-SVM	Least Squares Support Vector Machines
RF	Random Forest
LW	Local Order
WSNs	Wireless Sensor Networks
ROC	Receiver Operating Characteristic
MM	Migration Models
MGS	Membrane Gas Separation
HMT	Heat and Mass Transfer
SBM	Structural Behavior Models
SM	Stochastic Models
KRM	Kinetics Rate Models
CO_2	Carbon Dioxide
O_2	Oxygen
N_2	Nitrogen
H_2O	Water
FEA	Finite Element Analysis
MAP	Modified Atmosphere Packaging
1-MCP	Methyl Cyclopropane
TR	Transpiration Rate
CFD	Computational Fluid Dynamic
VCP	Ventilated Corrugated Paperboard
IoT	Internet of Things
GPS	Global Positioning System
NN	Neural Networks
NCP	Nano-Composite based Packaging
CFD	Computational Fluid Dynamics

References

1. Coulomb, D. Refrigeration and cold chain serving the global food industry and creating a better future: Two key IIR challenges for improved health and environment. *Trends Food Sci. Technol.* **2008**, *19*, 413–417. [CrossRef]
2. Shafiee-Jood, M.; Cai, X. Reducing Food Loss and Waste to Enhance Food Security and Environmental Sustainability. *Environ. Sci. Technol.* **2016**, *50*, 8432–8443. [CrossRef] [PubMed]
3. Gustavsson, J.; Stage, J. Retail waste of horticultural products in Sweden. *Resour. Conserv. Recycl.* **2011**, *55*, 554–556. [CrossRef]
4. Yahaya, S.; Ay, M. Review of Post-Harvest Losses of Fruits and Vegetables. *Biomed. J. Sci. Tech. Res.* **2019**, *13*, 10192–10200. [CrossRef]
5. Onwude, D.; Hashim, N.; Janius, R.; Nawi, N.; Khalina, A. Modeling the thin-layer drying of fruits and vegetables—A review. *Compr. Rev. Food Sci. Food Saf.* **2016**, *15*, 599–618. [CrossRef]
6. Salehi, F.; Aghajanzadeh, S. Effect of dried fruits and vegetables powder on cakes quality: A review. *Trends Food Sci. Technol.* **2020**, *95*, 162–172. [CrossRef]

7. Jiang, Q.; Zhang, M.; Xu, B. Application of ultrasonic technology in postharvested fruits and vegetables storage: A review. *Ultrason. Sonochem.* **2020**, *69*, 105261. [CrossRef]
8. Cömert, E.D.; Mogol, B.A.; Gökmen, V. Relationship between color and antioxidant capacity of fruits and vegetables. *Curr. Res. Food Sci.* **2020**, *2*, 1–10. [CrossRef] [PubMed]
9. Huang, L.l.; Zhang, M. Trends in Development of Dried Vegetable Products as Snacks. *Dry. Technol.* **2012**, *30*, 448–461. [CrossRef]
10. Liu, D.K.; Xu, C.C.; Guo, C.X.; Zhang, X.X. Sub-zero temperature preservation of fruits and vegetables: A review. *J. Food Eng.* **2019**, *275*, 109881. [CrossRef]
11. Mercier, S.; Villeneuve, S.; Mondor, M.; Uysal, I. Time–Temperature Management along the Food Cold Chain: A Review of Recent Developments. *Compr. Rev. Food Sci. Food Saf.* **2017**, *16*, 647–667. [CrossRef]
12. Arah, I.K.; Ahorbo, G.K.; Anku, E.K.; Kumah, E.K.; Amaglo, H. Postharvest Handling Practices and Treatment Methods for Tomato Handlers in Developing Countries: A Mini Review. *Adv. Agric.* **2016**, *2016*, 6436945. [CrossRef]
13. Raut, R.D.; Gardas, B.B.; Narwane, V.S.; Narkhede, B.E. Improvement in the food losses in fruits and vegetable supply chain—A perspective of cold third-party logistics approach. *Oper. Res. Perspect.* **2019**, *6*, 100117. [CrossRef]
14. James, S.J.; James, C. The food cold-chain and climate change. *Food Res. Int.* **2010**, *43*, 1944–1956. [CrossRef]
15. Defraeye, T.; Cronje, P.J.R.; Berry, T.; Opara, U.L.; East, A.; Hertog, M.L.A.T.M.; Verboven, P.; Nicolai, B.M. Towards integrated performance evaluation of future packaging for fresh produce in the cold chain. *Trends Food Sci. Technol.* **2015**, *44*, 201–225. [CrossRef]
16. Thompson, J.F.; Mejia, D.C.; Singh, R.P. Energy Use of Commercial Forced-Air Coolers for Fruit. *Appl. Eng. Agric.* **2010**, *26*, 919–924. [CrossRef]
17. Piljac-Žegarac, J.; Šamec, D. Antioxidant stability of small fruits in postharvest storage at room and refrigerator temperatures. *Food Res. Int.* **2011**, *44*, 345–350. [CrossRef]
18. Chu, W.; Gao, H.; Chen, H.; Wu, W.-J.; Fang, X. Changes in Cuticular Wax Composition of Two Blueberry Cultivars during Fruit Ripening and Postharvest Cold Storage. *J. Agric. Food Chem.* **2018**, *66*, 2870–2876. [CrossRef]
19. Fagundes, C.; Moraes, K.; Pérez-Gago, M.; Palou, L.; Maraschin, M.; Monteiro, A. Effect of active modified atmosphere and cold storage on the postharvest quality of cherry tomatoes. *Postharvest Biol. Technol.* **2015**, *109*, 73–81. [CrossRef]
20. Hong, K.; Xie, J.; Zhang, L.; Sun, D.; Gong, D. Effects of chitosan coating on postharvest life and quality of guava (*Psidium guajava* L.) fruit during cold storage. *Sci. Hortic.* **2012**, *144*, 172–178. [CrossRef]
21. Hu, Q.; Fang, Y.; Yang, Y.; Ma, N.; Zhao, L. Effect of nanocomposite-based packaging on postharvest quality of ethylene-treated kiwifruit (*Actinidia deliciosa*) during cold storage. *Food Res. Int.* **2011**, *44*, 1589–1596. [CrossRef]
22. Jiang, T.; Feng, L.; Li, J. Changes in microbial and postharvest quality of shiitake mushroom (*Lentinus edodes*) treated with chitosan–glucose complex coating under cold storage. *Food Chem.* **2012**, *131*, 780–786. [CrossRef]
23. Zhang, Y.; Zhang, M.; Yang, H. Postharvest chitosan-g-salicylic acid application alleviates chilling injury and preserves cucumber fruit quality during cold storage. *Food Chem.* **2015**, *174*, 558–563. [CrossRef]
24. Ghaani, M.; Cozzolino, C.A.; Castelli, G.; Farris, S. An overview of the intelligent packaging technologies in the food sector. *Trends Food Sci. Technol.* **2016**, *51*, 1–11. [CrossRef]
25. Müller, P.; Schmid, M. Intelligent Packaging in the Food Sector: A Brief Overview. *Foods* **2019**, *8*, 16. [CrossRef] [PubMed]
26. Haass, R.; Dittmer, P.; Veigt, M.; Lütjen, M. Reducing food losses and carbon emission by using autonomous control—A simulation study of the intelligent container. *Int. J. Prod. Econ.* **2015**, *164*, 400–408. [CrossRef]
27. Janjarasskul, T.; Suppakul, P. Active and intelligent packaging: The indication of quality and safety. *Crit. Rev. Food Sci. Nutr.* **2017**, *58*, 808–831. [CrossRef]
28. Williams, H.; Wikström, F. Environmental impact of packaging and food losses in a life cycle perspective: A comparative analysis of five food items. *J. Clean. Prod.* **2011**, *19*, 43–48. [CrossRef]
29. White, A.; Lockyer, S. Removing plastic packaging from fresh produce—What's the impact? *Nutr. Bull.* **2020**, *45*, 35–50. [CrossRef]
30. Bilstein, F. What Reduces Our Personal CO_2 Footprint? We Have no Clue! 2019. Available online: https://www.linkedin.com/pulse/what-reduces-our-personal-co2-footprint-we-have-clue-frank-bilstein (accessed on 19 October 2020).

31. Wynes, S.; A Nicholas, K. The climate mitigation gap: Education and government recommendations miss the most effective individual actions. *Environ. Res. Lett.* **2017**, *12*, 074024. [CrossRef]
32. Hischier, R. Schwierige Suche Nach Plastikalternativen. *Migros Mag.* **2019**. Available online: https://www.migrosmagazin.ch/schwierige-suche-nach-plastikalternativen (accessed on 19 October 2020).
33. Conte, A.; Cappelletti, G.; Nicoletti, G.; Russo, C.; Del Nobile, M. Environmental implications of food loss probability in packaging design. *Food Res. Int.* **2015**, *78*, 11–17. [CrossRef]
34. Gutierrez, M.M.; Meleddu, M.; Piga, A. Food losses, shelf life extension and environmental impact of a packaged cheesecake: A life cycle assessment. *Food Res. Int.* **2017**, *91*, 124–132. [CrossRef]
35. Denkstatt. How Packaging Contributes to Food Waste Prevention. 2017. Available online: www.denkstatt.at (accessed on 19 October 2020).
36. Duan, Y.; Wang, G.-B.; Fawole, O.A.; Verboven, P.; Zhang, X.-R.; Wu, D.; Opara, U.L.; Nicolai, B.; Chen, K. Postharvest precooling of fruit and vegetables: A review. *Trends Food Sci. Technol.* **2020**, *100*, 278–291. [CrossRef]
37. Praeger, U.; Jedermann, R.; Sellwig, M.; Neuwald, D.A.; Hartgenbusch, N.; Borysov, M.; Truppel, I.; Scaar, H.; Geyer, M. Airflow distribution in an apple storage room. *J. Food Eng.* **2020**, *269*, 109746. [CrossRef]
38. Badia-Melis, R.; Carthy, U.M.; Ruiz-Garcia, L.; Garcia-Hierro, J.; Villalba, J.I.R. New trends in cold chain monitoring applications—A review. *Food Control* **2018**, *86*, 170–182. [CrossRef]
39. Gustavsson, J.; Cederberg, C.; Sonesson, U.; van Otterdijk, R.; Meybeck, A. *Global Food Losses and Food Waste*; FAO: Rome, Italy, 2011.
40. Morris, K.J.; Kamarulzaman, N.H.; I Morris, K. Small-scale postharvest practices among plantain farmers and traders: A potential for reducing losses in rivers state, Nigeria. *Sci. Afr.* **2019**, *4*, e00086. [CrossRef]
41. Parfitt, J.; Barthel, M.; Macnaughton, S. Food waste within food supply chains: Quantification and potential for change to 2050. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 3065–3081. [CrossRef]
42. Lundqvist, J.; de Fraiture, C.; Molden, D. *Saving Water: From Field to Fork: Curbing Losses and Wastage in the Food Chain*; Stockholm International Water Institute: Stockholm, Sweden, 2008.
43. Bustos, C.A.; Moors, E.H. Reducing post-harvest food losses through innovative collaboration: Insights from the Colombian and Mexican avocado supply chains. *J. Clean. Prod.* **2018**, *199*, 1020–1034. [CrossRef]
44. Santos, S.F.; Cardoso, R.D.C.V.; Borges, Í.M.P.; Almeida, E.A.C.; Andrade, E.S.; Dos Santos, S.F.; Ramos, L.D.C. Post-harvest losses of fruits and vegetables in supply centers in Salvador, Brazil: Analysis of determinants, volumes and reduction strategies. *Waste Manag.* **2019**, *101*, 161–170. [CrossRef]
45. FAO. *Food Wastage Footprint—Impacts on Natural Resources: Summary Report*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2013.
46. Sivakumar, D.; Wall, M.M. Papaya Fruit Quality Management during the Postharvest Supply Chain. *Food Rev. Int.* **2013**, *29*, 24–48. [CrossRef]
47. Mampholo, B.M.; Sivakumar, D.; Thompson, A.K. Maintaining overall quality of fresh traditional leafy vegetables of Southern Africa during the postharvest chain. *Food Rev. Int.* **2015**, *32*, 400–416. [CrossRef]
48. Bradford, K.J.; Dahal, P.; Van Asbrouck, J.; Kunusoth, K.; Bello, P.; Thompson, J.; Wu, F. The dry chain: Reducing postharvest losses and improving food safety in humid climates. *Trends Food Sci. Technol.* **2018**, *71*, 84–93. [CrossRef]
49. Gordon, A.; Gordon, D. Food safety and quality systems implementation along value chains. In *Food Safety and Quality Systems in Developing Countries*; Elsevier BV: Amsterdam, The Netherlands, 2020; pp. 81–124.
50. Canadian Food Inspection Agency. *Food Safety Enhancement Program Manual*; Canadian Food Inspection Agency: Ottawa, ON, Canada, 2014.
51. Siripatrawan, U. Hyperspectral imaging for rapid evaluation and visualization of quality deterioration index of vacuum packaged dry-cured sausages. *Sensors Actuators B Chem.* **2018**, *254*, 1025–1032. [CrossRef]
52. Dowlati, M.; De La Guardia, M.; Mohtasebi, S.S. Application of machine-vision techniques to fish-quality assessment. *TrAC Trends Anal. Chem.* **2012**, *40*, 168–179. [CrossRef]
53. Feng, Y.Z.; Sun, D.-W. Determination of total viable count (TVC) in chicken breast fillets by near-infrared hyperspectral imaging and spectroscopic transforms. *Talanta* **2013**, *105*, 244–249. [CrossRef]
54. Aghbashlo, M.; Hosseinpour, S.; Ghasemi-Varnamkhasti, M. Computer vision technology for real-time food quality assurance during drying process. *Trends Food Sci. Technol.* **2014**, *39*, 76–84. [CrossRef]
55. Martynenko, A. Computer Vision for Real-Time Control in Drying. *Food Eng. Rev.* **2017**, *9*, 91–111. [CrossRef]

56. Zhang, H.; Li, D. Applications of computer vision techniques to cotton foreign matter inspection: A review. *Comput. Electron. Agric.* **2014**, *109*, 59–70. [CrossRef]
57. Zhang, B.; Huang, W.; Li, J.; Zhao, C.; Fan, S.; Wu, J.; Liu, C. Principles, developments and applications of computer vision for external quality inspection of fruits and vegetables: A review. *Food Res. Int.* **2014**, *62*, 326–343. [CrossRef]
58. Agudelo-Laverde, L.M.; Schebor, C.; Buera, M. Water content effect on the chromatic attributes of dehydrated strawberries during storage, as evaluated by image analysis. *LWT-Food Sci. Technol.* **2013**, *52*, 157–162. [CrossRef]
59. Cubero, S.; Aleixos, N.; Moltó, E.; Gómez-Sanchis, J.; Blasco, J. Advances in Machine Vision Applications for Automatic Inspection and Quality Evaluation of Fruits and Vegetables. *Food Bioprocess Technol.* **2010**, *4*, 487–504. [CrossRef]
60. Li, Y.; Tang, X.; Shen, Z.; Dong, J. Prediction of total volatile basic nitrogen (TVB-N) content of chilled beef for freshness evaluation by using viscoelasticity based on airflow and laser technique. *Food Chem.* **2019**, *287*, 126–132. [CrossRef]
61. Sanaeifar, A.; Zakidizaji, H.; Jafari, A.; De La Guardia, M. Early detection of contamination and defect in foodstuffs by electronic nose: A review. *TrAC Trends Anal. Chem.* **2017**, *97*, 257–271. [CrossRef]
62. Emana, B.; Afari-Sefa, V.; Nenguwo, N.; Ayana, A.; Kebede, D.; Mohammed, H. Characterization of pre- and postharvest losses of tomato supply chain in Ethiopia. *Agric. Food Secur.* **2017**, *6*, 87. [CrossRef]
63. Pace, B.; Cefola, M.; Da Pelo, P.; Renna, F.; Attolico, G. Non-destructive evaluation of quality and ammonia content in whole and fresh-cut lettuce by computer vision system. *Food Res. Int.* **2014**, *64*, 647–655. [CrossRef] [PubMed]
64. Fukuda, S.; Yasunaga, E.; Nagle, M.; Yuge, K.; Sardsud, V.; Spreer, W.; Müller, J. Modelling the relationship between peel colour and the quality of fresh mango fruit using Random Forests. *J. Food Eng.* **2014**, *131*, 7–17. [CrossRef]
65. Cavallo, D.P.; Cefola, M.; Pace, B.; Logrieco, A.F.; Attolico, G. Non-destructive automatic quality evaluation of fresh-cut iceberg lettuce through packaging material. *J. Food Eng.* **2018**, *223*, 46–52. [CrossRef]
66. Cavallo, D.P.; Cefola, M.; Pace, B.; Logrieco, A.F.; Attolico, G. Non-destructive and contactless quality evaluation of table grapes by a computer vision system. *Comput. Electron. Agric.* **2019**, *156*, 558–564. [CrossRef]
67. Amigo, J.M.; Santos, C. Preprocessing of hyperspectral and multispectral images. *Data Handl. Sci. Technol.* **2020**, *32*, 37–53. [CrossRef]
68. Marini, F.; Amigo, J.M. Unsupervised exploration of hyperspectral and multispectral images. *Data Handl. Sci. Technol.* **2020**, *32*, 93–114. [CrossRef]
69. Nicolaï, B.M.; Beullens, K.; Bobelyn, E.; Peirs, A.; Saeys, W.; Theron, K.I.; Lammertyn, J. Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy: A review. *Postharvest Biol. Technol.* **2007**, *46*, 99–118. [CrossRef]
70. Hashim, N.; Onwude, D.; Osman, M.S. Evaluation of Chilling Injury in Mangoes Using Multispectral Imaging. *J. Food Sci.* **2018**, *83*, 1271–1279. [CrossRef]
71. Ruiz-Altisent, M.; Ruiz-Garcia, L.; Moreda, G.; Lu, R.; Hernandez-Sanchez, N.; Correa, E.; Diezma, B.; Nicolaï, B.; García-Ramos, J. Sensors for product characterization and quality of specialty crops—A review. *Comput. Electron. Agric.* **2010**, *74*, 176–194. [CrossRef]
72. Lara, M.A.; Lleó, L.; Iglesias, B.D.; Roger, J.; Altisent, M.R. Monitoring spinach shelf-life with hyperspectral image through packaging films. *J. Food Eng.* **2013**, *119*, 353–361. [CrossRef]
73. Taghizadeh, M.; Gowen, A.; Ward, P.; O'Donnell, C.P. Use of hyperspectral imaging for evaluation of the shelf-life of fresh white button mushrooms (Agaricus bisporus) stored in different packaging films. *Innov. Food Sci. Emerg. Technol.* **2010**, *11*, 423–431. [CrossRef]
74. Liu, Y.; Chen, Y.R.; Wang, C.Y.; Chan, D.E.; Kim, M.S. Development of hyperspectral imaging technique for the detection of chilling injury in cucumbers; spectral and image analysis. *Appl. Eng. Agric.* **2006**, *22*, 101–111. [CrossRef]
75. Rivera, N.V.; Gómez-Sanchis, J.; Chanona-Pérez, J.; Carrasco, J.J.; Millán-Giraldo, M.; Lorente, D.; Cubero, S.; Blasco, J. Early detection of mechanical damage in mango using NIR hyperspectral images and machine learning. *Biosyst. Eng.* **2014**, *122*, 91–98. [CrossRef]

76. Panagou, E.Z.; Papadopoulou, O.; Carstensen, J.M.; Stamatiou, A. Potential of multispectral imaging technology for rapid and non-destructive determination of the microbiological quality of beef filets during aerobic storage. *Int. J. Food Microbiol.* **2014**, *174*, 1–11. [CrossRef] [PubMed]
77. Du, D.; Wang, J.; Wang, B.; Zhu, L.; Hong, X. Ripeness Prediction of Postharvest Kiwifruit Using a MOS E-Nose Combined with Chemometrics. *Sensors* **2019**, *19*, 419. [CrossRef]
78. Al-Sanabani, D.G.A.; Solihin, M.I.; Pui, L.P.; Astuti, W.; Ang, C.K.; Hong, L.W. Development of non-destructive mango assessment using Handheld Spectroscopy and Machine Learning Regression. *J. Phys. Conf. Ser.* **2019**, *1367*, 012030. [CrossRef]
79. Van de Looverbosch, T.; Bhuiyan, H.R.; Verboven, P.; Dierick, M.; Van Loo, D.; De Beenbouwer, J.; Sijbers, J.; Nicolaï, B. Nondestructive internal quality inspection of pear fruit by X-ray CT using machine learning. *Food Control* **2020**, *113*, 107170. [CrossRef]
80. Einarsdottir, H. Image Analysis for X-ray Imaging of Food. Ph.D. Thesis, Technical University of Denmark, Kongens Lyngby, Denmark, 2016.
81. Ghasemi-Varnamkhasti, M.; Apetrei, C.; Lozano, J.; Anyogu, A. Potential use of electronic noses, electronic tongues and biosensors as multisensor systems for spoilage examination in foods. *Trends Food Sci. Technol.* **2018**, *80*, 71–92. [CrossRef]
82. Fortuna, L.; Graziani, S.; Rizzo, A.; Xibilia, M.G. *Soft Sensors for Monitoring and Control of Industrial Processes*; Springer Science & Business Media: Berlin, Germany, 2007.
83. Liu, Z.; Jia, X.; Xu, X. Study of shrimp recognition methods using smart networks. *Comput. Electron. Agric.* **2019**, *165*, 104926. [CrossRef]
84. Liu, J.; Zhang, X.; Li, Z.; Zhang, X.; Jemrić, T.; Wang, X. Quality Monitoring and Analysis of Xinjiang 'Korla' Fragrant Pear in Cold Chain Logistics and Home Storage with Multi-Sensor Technology. *Appl. Sci.* **2019**, *9*, 3895. [CrossRef]
85. Feng, C.; Drummond, L.; Zhang, Z.; Sun, D.-W.; Wang, Q. Vacuum Cooling of Meat Products: Current State-of-the-Art Research Advances. *Crit. Rev. Food Sci. Nutr.* **2012**, *52*, 1024–1038. [CrossRef]
86. Lashgari, M.; Maleki, A.; Amiriparian, J. Application of acoustic impulse response in discrimination of apple storage time using neural network. *Int. Food Res. J.* **2017**, *24*, 1075.
87. Zou, Z.; Chen, Q.; Uysal, I.; Zheng, L. Radio frequency identification enabled wireless sensing for intelligent food logistics. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2014**, *372*, 20130313. [CrossRef]
88. Badia-Melis, R.; Ruiz-García, L.; Garcia-Hierro, J.; Villalba, J.I.R. Refrigerated Fruit Storage Monitoring Combining Two Different Wireless Sensing Technologies: RFID and WSN. *Sensors* **2015**, *15*, 4781–4795. [CrossRef]
89. Grunow, M.; Piramuthu, S. RFID in highly perishable food supply chains—Remaining shelf life to supplant expiry date? *Int. J. Prod. Econ.* **2013**, *146*, 717–727. [CrossRef]
90. Tian, F. An agri-food supply chain traceability system for China based on RFID & blockchain technology. In Proceedings of the 2016 13th International Conference on Service Systems and Service Management (ICSSSM), Kunming, China, 24–26 June 2016. [CrossRef]
91. Liao, Y.; Zhang, R.; Qian, J. Printed electronics based on inorganic conductive nanomaterials and their applications in intelligent food packaging. *RSC Adv.* **2019**, *9*, 29154–29172. [CrossRef]
92. Lipińska, M.; Tomaszewska, M.; Kołożyn-Krajewska, D. Identifying Factors Associated with Food Losses during Transportation: Potentials for Social Purposes. *Sustainability* **2019**, *11*, 2046. [CrossRef]
93. Badia-Melis, R.; Qian, J.P.; Fan, B.L.; Hoyos-Echevarria, P.; Ruiz-García, L.; Yang, X.T. Artificial Neural Networks and Thermal Image for Temperature Prediction in Apples. *Food Bioprocess Technol.* **2016**, *9*, 1089–1099. [CrossRef]
94. Castell-Palou, A.; Simal, S. Heat pump drying kinetics of a pressed type cheese. *LWT* **2011**, *44*, 489–494. [CrossRef]
95. Hertog, M.L.A.T.M.; Uysal, I.; McCarthy, U.; Verlinden, B.M.; Nicolaï, B.M. Shelf life modelling for first-expired-first-out warehouse management. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2014**, *372*, 20130306. [CrossRef]
96. Wu, W.; Cronje, P.J.; Nicolai, B.; Verboven, P.; Opara, U.L.; Defraeye, T. Virtual cold chain method to model the postharvest temperature history and quality evolution of fresh fruit—A case study for citrus fruit packed in a single carton. *Comput. Electron. Agric.* **2018**, *144*, 199–208. [CrossRef]

97. Song, Y.; Hu, Q.; Wu, Y.; Pei, F.; Kimatu, B.M.; Su, A.; Yang, W. Storage time assessment and shelf-life prediction models for postharvest *Agaricus bisporus*. *LWT* **2019**, *101*, 360–365. [CrossRef]
98. Ktenioudaki, A.; O'Donnell, C.P.; Nunes, M.C.D.N. Modelling the biochemical and sensory changes of strawberries during storage under diverse relative humidity conditions. *Postharvest Biol. Technol.* **2019**, *154*, 148–158. [CrossRef]
99. Zou, J.; Li, P. Modelling of litchi shelf life based on the entropy weight method. *Food Packag. Shelf Life* **2020**, *25*, 100509. [CrossRef]
100. Ambaw, A.; Verboven, P.; Defraeye, T.; Tijskens, E.; Schenk, A.; Opara, U.L.; Nicolai, B.M. Porous medium modeling and parameter sensitivity analysis of 1-MCP distribution in boxes with apple fruit. *J. Food Eng.* **2013**, *119*, 13–21. [CrossRef]
101. Delele, M.A.; Ngcobo, M.E.K.; Opara, U.L.; Meyer, C.J. Investigating the Effects of Table Grape Package Components and Stacking on Airflow, Heat and Mass Transfer Using 3-D CFD Modelling. *Food Bioprocess Technol.* **2012**, *6*, 2571–2585. [CrossRef]
102. Kim, W.R.; Aung, M.M.; Chang, Y.S.; Makatsoris, H. Freshness Gauge based cold storage management: A method for adjusting temperature and humidity levels for food quality. *Food Control.* **2015**, *47*, 510–519. [CrossRef]
103. Jedermann, R.; Praeger, U.; Geyer, M.; Lang, W. Remote quality monitoring in the banana chain. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2014**, *372*, 20130303. [CrossRef]
104. Hoang, M.H.; Laguerre, O.; Moureh, J.; Flick, D.; Hoang, H. Heat transfer modelling in a ventilated cavity loaded with food product: Application to a refrigerated vehicle. *J. Food Eng.* **2012**, *113*, 389–398. [CrossRef]
105. Defraeye, T.; Lambrecht, R.; Delele, M.; Ambaw, A.; Opara, U.L.; Cronje, P.J.; Verboven, P.; Nicolai, B. Forced-convective cooling of citrus fruit: Cooling conditions and energy consumption in relation to package design. *J. Food Eng.* **2014**, *121*, 118–127. [CrossRef]
106. Laguerre, O.; Düret, S.; Hoang, H.; Guillier, L.; Flick, D. Simplified heat transfer modeling in a cold room filled with food products. *J. Food Eng.* **2015**, *149*, 78–86. [CrossRef]
107. Escuela, G.; Hinze, T.; Dittrich, P.; Schuster, S. Modelling Modified Atmosphere Packaging for Fruits and Vegetables Using Membrane Systems. In Proceedings of the International Conference on Bio-inspired Systems and Signal Processing 2010, Valencia, Spain, 20–23 January 2010; pp. 306–311. [CrossRef]
108. Ahsan, M.; Hussain, A. A comparison of numerical methods used to solve cross flow model for multicomponent membrane gas separation. *World Appl. Sci. J.* **2013**, *22*, 703–711. [CrossRef]
109. Walawender, W.P.; Stern, S.A. Analysis of Membrane Separation Parameters. II. Counter-current and Cocurrent Flow in a Single Permeation Stage. *Sep. Sci.* **1972**, *7*, 553–584. [CrossRef]
110. Szwast, M.; Szwast, Z. A Mathematical Model of Membrane Gas Separation with Energy Transfer by Molecules of Gas Flowing in a Channel to Molecules Penetrating this Channel from the Adjacent Channel. *Chem. Process. Eng.* **2015**, *36*, 151–169. [CrossRef]
111. Xanthopoulos, G.; Koronaki, E.; Boudouvis, A. Mass transport analysis in perforation-mediated modified atmosphere packaging of strawberries. *J. Food Eng.* **2012**, *111*, 326–335. [CrossRef]
112. Dehghannya, J.; Ngadi, M.; Vigneault, C. Mathematical modeling of airflow and heat transfer during forced convection cooling of produce considering various package vent areas. *Food Control* **2011**, *22*, 1393–1399. [CrossRef]
113. Cevoli, C.; Fabbri, A. Heat transfer finite element model of fresh fruit salad insulating packages in non-refrigerated conditions. *Biosyst. Eng.* **2017**, *153*, 89–98. [CrossRef]
114. Choi, S.J.; Burgess, G. Practical mathematical model to predict the performance of insulating packages. *Packag. Technol. Sci.* **2007**, *20*, 369–380. [CrossRef]
115. De Cursi, E.S.; Sampaio, R. Introduction. In *Uncertainty Quantification and Stochastic Modeling with Matlab*; Elsevier Science: Amsterdam, The Netherlands, 2015; pp. 11–13. [CrossRef]
116. Ho, Q.T.; Rogge, S.; Verboven, P.; Verlinden, B.E.; Nicolaï, B.M. Stochastic modelling for virtual engineering of controlled atmosphere storage of fruit. *J. Food Eng.* **2016**, *176*, 77–87. [CrossRef]
117. Valentas, K.; Singh, R.P.; Rotstein, E. *Handbook of Food Engineering Practice*; Informa UK Limited: London, UK, 1997.
118. Zülch, A.; Piringer, O. Measurement and modelling of migration from paper and board into foodstuffs and dry food simulants. *Food Addit. Contam. Part A* **2010**, *27*, 1306–1324. [CrossRef]

119. Montanez, J.C.; Rodríguez, F.A.; Mahajan, P.V.; Frias, J. Modelling the gas exchange rate in perforation-mediated modified atmosphere packaging: Effect of the external air movement and tube dimensions. *J. Food Eng.* **2010**, *97*, 79–86. [CrossRef]
120. Poças, M.F.; Oliveira, J.C.; Pereira, J.R.; Brandsch, R.; Hogg, T. Modelling migration from paper into a food simulant. *Food Control* **2011**, *22*, 303–312. [CrossRef]
121. Xanthopoulos, G.; Mitropoulos, D.; Lambrinos, G. Estimation of Heat and Mass Transfer Coefficients During Air-Freezing of Cucumber. *Int. J. Food Prop.* **2012**, *15*, 221–235. [CrossRef]
122. Pandey, S.K.; Goswami, T.K. Modelling perforated mediated modified atmospheric packaging of capsicum. *Int. J. Food Sci. Technol.* **2012**, *47*, 556–563. [CrossRef]
123. Dehghannya, J.; Ngadi, M.; Vigneault, C. Transport phenomena modelling during produce cooling for optimal package design: Thermal sensitivity analysis. *Biosyst. Eng.* **2012**, *111*, 315–324. [CrossRef]
124. Delele, M.A.; Ngcobo, M.; Getahun, S.; Chen, L.; Mellmann, J.; Opara, U.L. Studying airflow and heat transfer characteristics of a horticultural produce packaging system using a 3-D CFD model. Part I: Model development and validation. *Postharvest Biol. Technol.* **2013**, *86*, 536–545. [CrossRef]
125. Chong, K.L.; Peng, N.; Yin, H.; Lipscomb, G.G.; Chung, T.-S.; Chung, T.-S. Food sustainability by designing and modelling a membrane controlled atmosphere storage system. *J. Food Eng.* **2013**, *114*, 361–374. [CrossRef]
126. Ambaw, A.; Verboven, P.; Defraeye, T.; Tijskens, E.; Schenk, A.; Opara, U.L.; Nicolai, B. Effect of box materials on the distribution of 1-MCP gas during cold storage: A CFD study. *J. Food Eng.* **2013**, *119*, 150–158. [CrossRef]
127. Sousa-Gallagher, M.J.; Mahajan, P.; Mezdad, T. Engineering packaging design accounting for transpiration rate: Model development and validation with strawberries. *J. Food Eng.* **2013**, *119*, 370–376. [CrossRef]
128. Ambaw, A.; Verboven, P.; Delele, M.A.; Defraeye, T.; Tijskens, E.; Schenk, A.; Nicolaï, B.M.; Ambaw, A. CFD Modelling of the 3D Spatial and Temporal Distribution of 1-methylcyclopropene in a Fruit Storage Container. *Food Bioprocess Technol.* **2012**, *6*, 2235–2250. [CrossRef]
129. Chaix, E.; Broyart, B.; Couvert, O.; Guillaume, C.; Gontard, N.; Guillard, V. Mechanistic model coupling gas exchange dynamics and Listeria monocytogenes growth in modified atmosphere packaging of non respiring food. *Food Microbiol.* **2015**, *51*, 192–205. [CrossRef]
130. Castellanos, D.A.; Cerisuelo, J.P.; Hernandez-Muñoz, P.; Herrera, A.; Gavara, R. Modelling the evolution of O2 and CO2 concentrations in MAP of a fresh product: Application to tomato. *J. Food Eng.* **2016**, *168*, 84–95. [CrossRef]
131. Castellanos, D.A.; Herrera, D.R.; Herrera, A.O. Modelling water vapour transport, transpiration and weight loss in a perforated modified atmosphere packaging for feijoa fruits. *Biosyst. Eng.* **2016**, *151*, 218–230. [CrossRef]
132. Fadiji, T.; Coetzee, C.; Opara, U.L. Compression strength of ventilated corrugated paperboard packages: Numerical modelling, experimental validation and effects of vent geometric design. *Biosyst. Eng.* **2016**, *151*, 231–247. [CrossRef]
133. Fadiji, T.S.; Berry, T.M.; Opara, U.L. Investigating the Mechanical Properties of Paperboard Packaging Material for Handling Fresh Produce under Different Environmental Conditions: Experimental Analysis and Finite Element Modelling Investigating the Mechanical Properties of Paperboard Packaging. *J. Appl. Packag. Res.* **2017**, *9*, 1–32.
134. Gruyters, W.; Verboven, P.; Diels, E.; Rogge, S.; Smeets, B.; Ramon, H.; Defraeye, T.; Nicolaï, B.M. Modelling Cooling of Packaged Fruit Using 3D Shape Models. *Food Bioprocess Technol.* **2018**, *11*, 2008–2020. [CrossRef]
135. Han, J.W.; Qian, J.-P.; Zhao, C.-J.; Yang, X.; Fan, B.-L. Mathematical modelling of cooling efficiency of ventilated packaging: Integral performance evaluation. *Int. J. Heat Mass Transf.* **2017**, *111*, 386–397. [CrossRef]
136. Fadiji, T.; Ambaw, A.; Coetzee, C.J.; Berry, T.M.; Opara, U.L. Application of finite element analysis to predict the mechanical strength of ventilated corrugated paperboard packaging for handling fresh produce. *Biosyst. Eng.* **2018**, *174*, 260–281. [CrossRef]
137. Wu, W.; Defraeye, T. Identifying heterogeneities in cooling and quality evolution for a pallet of packed fresh fruit by using virtual cold chains. *Appl. Therm. Eng.* **2018**, *133*, 407–417. [CrossRef]
138. Getahun, S.; Ambaw, A.; Delele, M.; Meyer, C.J.; Opara, U.L. Experimental and Numerical Investigation of Airflow Inside Refrigerated Shipping Containers. *Food Bioprocess Technol.* **2018**, *11*, 1164–1176. [CrossRef]
139. Kolodziejczyk, M.; Smierciew, K.; Gagan, J.; Butrymowicz, D. Numerical Modelling of Heat and Mass Transfer in Vegetables Cold Storage. *Procedia Eng.* **2016**, *157*, 279–284. [CrossRef]

140. Marques, A.C.; Davies, G.; Evans, J.; Maidment, G.; Wood, I. Theoretical modelling and experimental investigation of a thermal energy storage refrigerator. *Energy* **2013**, *55*, 457–465. [CrossRef]
141. Broeze, J.; Guo, X.; Axmann, H.; Vollebregt, M. *A Systemic Approach for Trade-Off Analysis of Food Loss Reduction and Greenhouse Gas Emissions*; CCAFS: Wageningen, The Netherlands, 2019.
142. Pinheiro, J.; Alegria, C.; Abreu, M.; Gonçalves, E.M.; Silva, C.L. Kinetics of changes in the physical quality parameters of fresh tomato fruits (*Solanum lycopersicum*, cv. 'Zinac') during storage. *J. Food Eng.* **2013**, *114*, 338–345. [CrossRef]
143. Aiello, G.; La Scalia, G.; Micale, R. Simulation analysis of cold chain performance based on time–temperature data. *Prod. Plan. Control.* **2011**, *23*, 468–476. [CrossRef]
144. Gonalves, E.M.; Abreu, M.; Brandão, T.R.; Silva, C.L. Degradation kinetics of colour, vitamin C and drip loss in frozen broccoli (*Brassica oleracea* L. ssp. *Italica*) during storage at isothermal and non-isothermal conditions. *Int. J. Refrig.* **2011**, *34*, 2136–2144. [CrossRef]
145. Guo, P.; Han, M.; Cao, N.; Shen, Y. The Research on Innovative Application of E-Commerce in IoT Era. In Proceedings of the 2017 IEEE International Conference on Computational Science and Engineering (CSE) and IEEE International Conference on Embedded and Ubiquitous Computing (EUC), Institute of Electrical and Electronics Engineers (IEEE), Guangzhou, China, 21–24 July 2017; Volume 2, pp. 410–413.
146. Singh, S.; Singh, N. Internet of Things (IoT): Security challenges, business opportunities & reference architecture for E-commerce. In Proceedings of the 2015 International Conference on Green Computing and Internet of Things (ICGCIoT) 2015, Delhi, India, 8–10 October 2015; pp. 1577–1581. [CrossRef]
147. Zhong, R.Y.; Xu, C.; Chen, C.; Huang, G.Q. Big Data Analytics for Physical Internet-based intelligent manufacturing shop floors. *Int. J. Prod. Res.* **2015**, *55*, 2610–2621. [CrossRef]
148. Grgić, K.; Speh, I.; Hedi, I. A web-based IoT solution for monitoring data using MQTT protocol. In Proceedings of the 2016 International Conference on Smart Systems and Technologies (SST), Osijek, Croatia, 12–14 October 2016; pp. 249–253. [CrossRef]
149. Zhamanov, A.; Sakhiyeva, Z.; Suliyev, R.; Kaldykulova, Z. IoT smart campus review and implementation of IoT applications into education process of university. In Proceedings of the 2017 13th International Conference on Electronics, Computer and Computation (ICECCO), Piscataway, NJ, USA, 28–29 November 2017; pp. 1–4. [CrossRef]
150. Bagheri, M.; Movahed, S.H. The Effect of the Internet of Things (IoT) on Education Business Model. In Proceedings of the 2016 12th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS), Naples, Italy, 28 November–1 December 2016; pp. 435–441. [CrossRef]
151. He, J.; Lo, D.C.-T.; Xie, Y.; Lartigue, J. Integrating Internet of Things (IoT) into STEM undergraduate education: Case study of a modern technology infused courseware for embedded system course. In Proceedings of the 2016 IEEE Frontiers in Education Conference (FIE), Eire, PA, USA, 12–15 October 2016; Institute of Electrical and Electronics Engineers (IEEE): New York, NY, USA, 2016; pp. 1–9.
152. Mezghani, E.; Exposito, E.; Drira, K. A Model-Driven Methodology for the Design of Autonomic and Cognitive IoT-Based Systems: Application to Healthcare. *IEEE Trans. Emerg. Top. Comput. Intell.* **2017**, *1*, 224–234. [CrossRef]
153. Amato, A.; Coronato, A. An IoT-Aware architecture for smart healthcare coaching systems. *Proc. Int. Conf. Adv. Inf. Netw. Appl. AINA* **2017**, *2*, 1027–1034. [CrossRef]
154. Doukas, C.; Maglogiannis, I. Bringing IoT and Cloud Computing towards Pervasive Healthcare. In Proceedings of the 2012 Sixth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing, Palermo, Italy, 4–6 July 2012; pp. 922–926. [CrossRef]
155. Kim, S.; Kim, S. A multi-criteria approach toward discovering killer IoT application in Korea. *Technol. Forecast. Soc. Chang.* **2016**, *102*, 143–155. [CrossRef]
156. Amendola, S.; Lodato, R.; Manzari, S.; Occhiuzzi, C.; Marrocco, G. RFID Technology for IoT-Based Personal Healthcare in Smart Spaces. *IEEE Internet Things J.* **2014**, *1*, 144–152. [CrossRef]
157. Lee, B.M.; Ouyang, J. Intelligent Healthcare Service by using Collaborations between IoT Personal Health Devices. *Int. J. Bio Sci. Bio Technol.* **2014**, *6*, 155–164. [CrossRef]
158. Farahani, B.; Firouzi, F.; Chang, V.; Badaroglu, M.; Constant, N.; Mankodiya, K. Towards fog-driven IoT eHealth: Promises and challenges of IoT in medicine and healthcare. *Future Gener. Comput. Syst.* **2018**, *78*, 659–676. [CrossRef]

159. Shenoy, J.; Pingle, Y. IOT in Agriculture. In Proceedings of the 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), New Delhi, India, 16–18 March 2016; pp. 1456–1458.
160. Brewster, C.; Roussaki, I.; Kalatzis, N.; Doolin, K.; Ellis, K. IoT in Agriculture: Designing a Europe-Wide Large-Scale Pilot. *IEEE Commun. Mag.* **2017**, *55*, 26–33. [CrossRef]
161. Pang, Z.; Chen, Q.; Han, W.; Zheng, L. Value-centric design of the internet-of-things solution for food supply chain: Value creation, sensor portfolio and information fusion. *Inf. Syst. Front.* **2012**, *17*, 289–319. [CrossRef]
162. Naeem, H. Detection of Malicious Activities in Internet of Things Environment Based on Binary Visualization and Machine Intelligence. *Wirel. Pers. Commun.* **2019**, *108*, 2609–2629. [CrossRef]
163. European Commission: Information Society and Media. Internet of Things in 2020: A Roadmap for the Future. *Internet Things* **2020**, *22*, 97–114.
164. Dlodlo, N.; Kalezhi, J. The internet of things in agriculture for sustainable rural development. In Proceedings of the 2015 IEEE International Conference on Emerging Trends in Networks and Computer Communications (ETNCC), Windhoek, Namibia, 17–20 May 2015; pp. 13–18.
165. Tsang, Y.P.; Choy, K.; Wu, C.; Ho, G.; Lam, H.; Tang, V. An intelligent model for assuring food quality in managing a multi-temperature food distribution centre. *Food Control* **2018**, *90*, 81–97. [CrossRef]
166. Verdouw, C.; Kruize, J.W. Digital twins in farm management: Illustrations from the FIWARE accelerators SmartAgriFood and Fractals. In Proceedings of the 7th Asian-Australasian Conference on Precision Agriculture, Hamilton, New Zealand, 16 October 2017; pp. 1–5.
167. Ben-Daya, M.; Hassini, E.; Bahroun, Z. Internet of things and supply chain management: A literature review. *Int. J. Prod. Res.* **2017**, *57*, 4719–4742. [CrossRef]
168. Tzounis, A.; Katsoulas, N.; Bartzanas, T.; Kittas, C. Internet of Things in agriculture, recent advances and future challenges. *Biosyst. Eng.* **2017**, *164*, 31–48. [CrossRef]
169. Ramundo, L.; Taisch, M.; Terzi, S. State of the art of technology in the food sector value chain towards the IoT. In Proceedings of the 2016 IEEE 2nd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI), Piscataway, NJ, USA, 7–9 September 2016; pp. 1–6.
170. Popa, A.; Hnatiuc, M.; Paun, M.; Geman, O.; Hemanth, D.J.; Dorcea, D.; Son, L.H.; Ghita, S. An Intelligent IoT-Based Food Quality Monitoring Approach Using Low-Cost Sensors. *Symmetry* **2019**, *11*, 374. [CrossRef]
171. Zhang, Y.; Zhao, L.; Qian, C. Modeling of an IoT-enabled supply chain for perishable food with two-echelon supply hubs. *Ind. Manag. Data Syst.* **2017**, *117*, 1890–1905. [CrossRef]
172. Ghoshal, G. *Recent Trends in Active, Smart, and Intelligent Packaging for Food Products*; Elsevier Inc.: Amsterdam, The Netherlands, 2018.
173. Porat, R.; Lichter, A.; Terry, L.A.; Harker, R.; Buzby, J. Postharvest losses of fruit and vegetables during retail and in consumers' homes: Quantifications, causes, and means of prevention. *Postharvest Biol. Technol.* **2018**, *139*, 135–149. [CrossRef]
174. Fuertes, G.; Soto, I.; Carrasco, R.R.; Vargas, M.; Sabattin, J.; Lagos, C. Intelligent Packaging Systems: Sensors and Nanosensors to Monitor Food Quality and Safety. *J. Sens.* **2016**, *2016*, 4046061. [CrossRef]
175. Sohail, M.; Sun, D.-W.; Zhu, Z. Recent developments in intelligent packaging for enhancing food quality and safety. *Crit. Rev. Food Sci. Nutr.* **2018**, *58*, 2650–2662. [CrossRef]
176. Borchert, N.B.; Kerry, J.P.; Papkovsky, D.B. A CO_2 sensor based on Pt-porphyrin dye and FRET scheme for food packaging applications. *Sensors Actuators B Chem.* **2013**, *176*, 157–165. [CrossRef]
177. Xiao, X.; Fu, Z.; Zhang, X.; Cheng, J.; Yang, M. Battery-free wireless sensor system with compressed sensing for table grapes cold chain. *Comput. Electron. Agric.* **2019**, *163*, 104869. [CrossRef]
178. Maksimović, M.; Vujović, V.; Omanović-Mikličanin, E. Application of internet of things in food packaging and transportation. *Int. J. Sustain. Agric. Manag. Inform.* **2015**, *1*, 333. [CrossRef]
179. Nukala, R.; Panduru, K.; Shields, A.; Riordan, D.; Doody, P.; Walsh, J. Internet of Things: A review from 'Farm to Fork'. In Proceedings of the 2016 27th IEEE Irish Signals and Systems Conference (ISSC), Derry, Ireland, 21–22 June 2016; pp. 1–6.
180. Bassi, A.; Bauer, M.; Fiedler, M.; Kranenburg, R.V. *Enabling Things to Talk*; Springer-Verlag GmbH: Berlin, Germany, 2013.
181. Verboven, P.; Verboven, P.; Defraeye, T.; Datta, A.K.; Nicolai, B. Digital twins of food process operations: The next step for food process models? *Curr. Opin. Food Sci.* **2020**, *35*, 79–87. [CrossRef]

182. Tao, F.; Cheng, J.; Qi, Q.; Zhang, M.; Zhang, H.; Sui, F. Digital twin-driven product design, manufacturing and service with big data. *Int. J. Adv. Manuf. Technol.* **2018**, *94*, 3563–3576. [CrossRef]
183. Uhlemann, T.H.J.; Schock, C.; Lehmann, C.; Freiberger, S.; Steinhilper, R. The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems. *Procedia Manuf.* **2017**, *9*, 113–120. [CrossRef]
184. Defraeye, T.; Tagliavini, G.; Wu, W.; Prawiranto, K.; Schudel, S.; Kerisima, M.A.; Verboven, P.; Bühlmann, A. Digital twins probe into food cooling and biochemical quality changes for reducing losses in refrigerated supply chains. *Resour. Conserv. Recycl.* **2019**, *149*, 778–794. [CrossRef]
185. Tagliavini, G.; Defraeye, T.; Carmeliet, J. Multiphysics modeling of convective cooling of non-spherical, multi-material fruit to unveil its quality evolution throughout the cold chain. *Food Bioprod. Process.* **2019**, *117*, 310–320. [CrossRef]
186. Furio, A.; Landi, G.; Altavilla, C.; Sofia, D.; Iannace, S.; Sorrentino, A.; Neitzert, H.C. Light irradiation tuning of surface wettability, optical, and electric properties of graphene oxide thin films. *Nanotechnology* **2016**, *28*, 54003. [CrossRef]
187. Cuello, J. Our Fresh-Produce Supply Chain after COVID-19: How vertical farming can play a key role. *Resour. Mag.* **2020**, *27*, 10–12.