Physiological processes affecting postharvest quality of fresh fruits and vegetables

Abstract

Fresh fruits and vegetables are integral components of a balanced diet, providing essential nutrients and contributing to human health. However, the postharvest quality of these perishable commodities is greatly influenced by various physiological processes that occur after harvest. This article reviews the key physiological processes affecting postharvest quality, including respiration, transpiration, ripening, senescence, and enzymatic activity. Understanding these processes is crucial for optimizing postharvest handling practices to extend shelf life, maintain quality attributes such as texture, flavor, color, and nutritional content, and minimize losses. Strategies to manage these physiological processes, including temperature and humidity control, modified atmosphere packaging, and the use of postharvest treatments, are discussed. Additionally, emerging technologies and innovative approaches for enhancing postharvest quality and extending the storage life of fresh fruits and vegetables are highlighted. By elucidating the complex interplay of physiological factors influencing postharvest quality, this abstract aims to provide valuable insights for researchers, practitioners, and stakeholders involved in the fresh produce supply chain, ultimately contributing to the promotion of food security and sustainability.

Key words: Postharvest physiology, Respiration, Transpiration, Ethylene

1.Introduction

After harvest, quality of fresh commodities begins to degenerate due to a mix of physical transport phenomena resulting to migration of water and other molecules in or out of the produce, adverse environmental exposures, microbial activities, and biochemical changes that accompany a respiring cell [1]. To ensure retention of the desirable qualities of fresh produce, after harvest, it is important that these factors are controlled, and their impacts minimised or eliminated, completely. In developing countries, the cost of applying available technologies to ensure preservation of fresh commodities and minimise the onset of degradation processes is remarkably high. This is because of lack of electricity and other inputs required to drive these systems.

2. Postharvest physiology of fresh commodities

The scientific study of live plant tissues after it has been deprived of further nutrients by plucking is known as postharvest physiology. Determining the ideal conditions for transport and storage to maximise shelf life has direct applicability to postharvest management [2]. Fresh produce keeps up their metabolic activities and physiological system after being picked. The losses from respiration and transpiration by fresh produce as it is affixed to the plant are replenished from the sap's flow. The sap holds water, simple sugars, and minerals [3]. Once, harvested or separated from the parent plants, produce continue to breath and loose moisture (transpiration) leading to quality degradation because of the inability to replenish themselves. As soon as harvested, fruits and vegetables gradually losses the ability to resist the biotic and abiotic physiological stressors which lead to spoilage if not controlled.

Postharvest handling begins at harvest and knowledge of the physiological processes of fresh commodities are critical to controlling and mitigating the onset of physiological changes that lead to quality degradation. Extremes in temperature, desiccation, microbiological invasion, gaseous environment, light, and mechanical handling are some of the factors implicated to cause physiological stress in fresh produce leading to deterioration [4]and moisture loss[5].Notably, losses after harvest can happen at any time in the cycle of the chains and commercialisation. These losses can vary from more than 10% in developed nations to more than 50% in tropical regions with little storage facilities [6]. The goals of post-harvest handling and protection are to avoid physical damage such as bruising, store produce at cool temperature, to slow down undesirable chemical changes.

The major factors responsible for the fresh fruit and vegetable decay is respiration, transpiration, and ethylene production. Technologies which reduce these degradation processes would ensure prolonged life of fresh produce.

3. Respiration

Like every living thing, fresh commodities respire. Respiration in fresh commodities is crucial to ensure the provision of energy needed to maintain and promote the metabolic process of the cells in fresh produce and occurs in the cytoplasm and mitochondrion of cells. Respiration involves oxidative catabolism of carbohydrates into water and carbon dioxide, with the liberation of adenosine triphosphate (ATP), an energy source and heat. The ATP is the energy currency of living cells including fresh commodities, which is responsible for activation of biochemical reactions within the cells. The equation for respiration reaction in living cells generates 36ATPs.

$$C_6H_{12}O_6 + 6O_2 + 36ADP \rightarrow 6CO_2 + 6\,H_2O + 36ATP \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

The relationship between postharvest shelf life and the rate of respiration of fresh commodities is inverse in correlation. On the other hand, storage situations, specifically in terms of its gaseous makeup, storage environment temperature, and relative humidity directly affects respiration rate. Up until a particular point, fruits and vegetables' respiration rates decreased when O_2 concentrations dropped, and CO_2 concentrations rose [7]. Table 1 shows the respiration rate of various perishable commodities.

Table 1Respiration rates of some fresh agricultural produce

Class	Range at 5 °C *mg CO_2 Kg^{-1} h^{-1}*	Commodities

Very Low	<5	Nuts, dates
Low	5 -10	Apple, citrus, grape, kiwifruit, onion, potato
Moderate	10-20	Apricot, banana, cherry, peach, nectarine, pear, plum, fig, cabbage, carrot, lettuce, pepper, and tomato
High	20-40	Strawberry, blackberry, raspberry, cauliflower, Lima bean, avocado
Very High	40-60	Artichoke, snap bean, Brussels sprouts, cut flowers
Extremely High	>60	Asparagus, broccoli, mushroom

Source: Saltveit[8].

In a complete respiration process, the amount of oxygen uptake is equivalent to the amount of CO_2 generated. The proportion of carbon dioxide generated to the oxygen consumed represents an index known as the **Respiratory Quotient**. Respiratory quotient varies with different substrates. The determination of molecules or a combination of molecules metabolisedcan be ascertained using this concept of respiratory quotient [9]. It has been confirmed that the respiratory quotient changes noticeably as fresh produce shifts from aerobic to anaerobic respiration. During anaerobic respiration, carbon dioxide is produced but no oxygen is consumed. It is possible to accurately determine the point at which a fresh fruit or vegetable switch from aerobic respiration to fermentation (otherwise regarded as anaerobic respiration) by experimental measurement of the proportion of CO_2 generated to oxygen utilised.

$$\text{Respiratory Quotient (RQ)} = \frac{\text{Carbon dioxide } (CO_2) \text{ Produced}}{\text{Oxygen } (O_2) \text{ Consumed}} \quad \ldots\ldots\ldots\ldots\ldots\ \ldots\ldots (2)$$

Thus, for aerobic respiration of glucose, the respiration quotient is equal to one (R = 1). For anaerobic respiration, no oxygen is consumed and therefore respiratory quotient (RQ) is equal to infinity (R = infinity) [9].

3.1 Measurement of respiration

The specific measure of the rate of metabolism of living tissues is respiratory gas exchange. This is because respiration is central to the overall metabolism of the plants. The rate of gas exchange of fresh produce otherwise known as respiration has been measured to a significant extent under carbon dioxide and oxygen conditions of the atmospheres, humidity, and temperature conditions. Information generated from these studies have been applied to determine best conditions for CA storage or with MA packaging [10].

Static, flowthrough, and modified atmosphere (MA) are the most popular methods used for determining gas exchange and thereby estimating the respiration rate.

- **Measurement by a static method.** In the static method, the fresh produce is enclosed to generate a specific gas composition in the sealed gas jar for a given time duration. The composition of gas is quantified at the start and culmination of the period and the difference calculated. The respiration rate is extrapolated using the change in air composition with time [11].

- **Measurement by flowthrough method.** Alternatively, the composition of gas of the inner and outward flow is determined using a flowthrough setup. In this setup, the fresh produce is confined into a space with an inlet and outlet. An inert gas of know composition is pass through the space and the composition of the outlet gas is measured. The quantity of carbon dioxide oxide emitted by the fresh produce is established by the makeup of the outlet gas and correlated to respiration rate with time [12].

- **Modified atmosphere method (MA).**This is done using a packaging material or film whose permeability characteristics for O_2 and CO_2 is known. The equilibrium concentration of the gas is allowed to be achieved and measured. The rate of exchange of gas can then be computed [11].

3.2 Factors affecting respiration rate

Factors affecting respiration rate of fresh produce includes both pre-harvest and postharvest conditions. The most crucial post-harvest elements are physical stress, composition of the atmosphere, and temperature. Other factors include but are not limited to chemical stress (for instance, fumigant), light, attack of pathogen, growth regulators and radiation stress [8].

- **Temperature:**respiration rate rises with an upsurge in the temperature of the storage space where the fresh commodity is stored. An increase in storage temperatures of crops results in an exponential rise in respiration above their physiological range, which is 0 to 30 °C (32 to 86 °F). The Van't Hoff Rule describes temperature's impact on a plant's rate of respiration. It states that every 10 degrees rise in temperature of the environment of fresh produce, there is a 2 to 3 times rise in the rate of `biochemical processes, such as respiration [8]. That is, for every 10^{o}C rise in temperature, the commodity's respiration rate doubles or triples. This correlation involving temperature and respiration rate is represented by the quotient represented as $Q_{10.}$ The temperature quotient abbreviated as $Q_{10}$is computed by division of rate of biochemical reaction at an elevated temperature by the reaction rate at 10 degrees. The equation is written as; $Q_{10} = R_2/R_1$ where R_2 = rate of reaction at elevated temperature and R_1 is the reaction rate at 10 ^{o}C. The rate of respiration can be calculated from the temperature quotient at a particular temperature from an established and reference rate at second distinct condition of temperature. Therefore, the temperature quotient is a piece of valuable information in the calculations of the respiration rate. The drawback of the use of temperate quotient for the determination of respiration rate is the fact the behaviourthe of rate of respiration is not ideal and varies with temperature. This means that Q_{10} also varies per temperature. Specifically, at elevated temperatures, the temperature quotient, Q_{10} is typically smaller. The reverse is the case for lower temperature as the Q_{10} is typically lager [8].

Clearly control and manipulation of storage temperatures is the most efficient approach for preserving quality of fresh commodities, and in turn prolong their shelf life. This is true as temperature affects rates of reactions which includes microbiological, biochemical, physical, and physiological degradation that results to postharvest losses [13]. Decreasing the temperature of fresh foods will reduce respiration rate and in turn slow down spoilage and degradation processes. Temperature management begins with harvesting, through packing house operation and to the unbroken cold chain of transportation and distribution to processing factories, retail outlets and final consumers. However, in the developing countries, the technology required for the keeping up with cold chain systems in handling of fruits and vegetables after harvest is seldom available or where available is very costly leading to inadequate return on investment to farmers. Also, in topics and subtropics, most fresh fruits and vegetables are affected by low temperature of chilling below 10-12^{o}C, unlike temperate fruits and vegetables which can withstand temperature 0^{o}C to 1^{o}C. These fruits experience chilling injury when they are cooled to chilling temperature leading to quality defects. The classification of fruits and vegetables into chill-sensitive and less chill-sensitive is presented in Table 2.

Table 2: Commodities and their degree of sensitivity to chilling injury

Chill-sensitive	Less chill-sensitive
Banana	Apple
Avocado	Pears
Citrus	Asparagus
Guava	Broccoli
Snap beans	Brussels sprouts
Tomato	Cauliflower
Aubergine	Onion
Mango	Peas

Source: Belwal*et al*. [14]

Conversely, exposure of fresh produce to temperatures above the physiological range will lead to heat stress. This results to fall in the rate of respiration and lead to thermal death point, resulting to alteration of metabolic reactions and denaturing of enzyme proteins of the produce.

- **Atmospheric gas composition:** Gas exchange in fresh commodities can result to respiration or fermentation. In the abundance of oxygen, respiration occurs and, in an oxygen-limited or carbon dioxide-rich environment, fermentation occurs. The consequence of air composition of the environment of fresh produce affects markedly the respiration rate and can be illustrated using the respiration equation.

$$C_6H_{12}O_6 \quad + \quad 6\ O_2 \quad \rightarrow \quad 6\ CO_2 \quad + \quad 6\ H_2O \quad \text{...} \quad (3)$$

Glucose   Oxygen   Carbon dioxide   Water

Reactants   Products

The rate of chemical reactions is affected by the concentration of the reactant(s) and product(s) in line with law of chemical equilibrium. A decline in the concentration of reactant(s) and/or rise in the concentration of products results to reduction in the rate of reaction. Applying this equilibrium theory to respiration, the reactants are sugars and O_2, and the products are CO_2 and water. Therefore, if the products environment O_2 concentration is reduced and/or CO_2 concentration is increased, the rate of respiration of the fresh produce will decrease commensurately. The concept of controlled atmosphere (CA) is hinged on this principle of effect of concentration of reactants and products on the rate of respiration. In conjunction with refrigeration, the controlled atmosphere is applied to control the atmospheric composition of air surrounding fresh commodities [15]. The molecular oxygen concentration in the natural atmosphere is about 21% and packing fresh produce in an airtight environment would result to depletion of oxygen in the surroundings and lead to decrease in the respiration rate, delayed senescence, and retard fungal growth [8]. A total absence of oxygen in the surrounding of the produce will lead to fermentation. Fermentation is an anaerobic respiration process that would result to conversion of pyruvic acid produced during glycolysis to acetaldehyde which if further reduced to ethanol or lactic acid. Energy is produced during fermentation, though, small when compared with energy produced during aerobic fermentation. Ethanol and lactic acid are toxic to the cells of produce and therefore in high concentrations can lead to cell death with the resultant quality loss and off-flavours. Different commodities have a varying critical concentration of molecular oxygen at which point anaerobic respiration is triggered. Most fruits have their critical concentration for oxygen as 1-

3%. Conversely, sweet potato roots require higher concentrations of oxygen at 5-7%, at this point the product will switch to anaerobic respiration [11].

- **Physical stress and damage:** Stress in the form of physical injury, bruises, and damage can lead to an increased respiration rate. This is the result of the effects of physical stress on ethylene production. Physical injury and damage accelerate ethylene production resulting in increased ripening, senescence, and final deterioration. In addition to increased ethylene production, the rate of respiration is increased when produce is physically damaged or is infected by rotting pathogens. The acceleration of breathing rate when the physical injury occurs is, as a result, the defense and repair mechanism of tissues. Mobilisation of various defense and repair mechanisms requires additional energy and hence the rise in the rate of respiration, with concomitant effects on stored produce [8].

3.3 Control of respiration

To reduce loss from excessive respiration, scientists over the years have invented different methods to control and slow the propensity of respiration in fresh produce fruits. Decrease in the speed of respiration is mostly achieved through the process of the altered or modified atmosphere [11]. Apart from reduction in respiration rate, lowering O_2 and increased carbon IV oxide in the surroundings of fresh fruits affect ethylene production and suppress microbial growth. Packaging with a MA and storage in a CA are the most common method of achieving a reduction in respiration rate by altering the gas makeup in the environment of the fresh commodities. Storage under a regulated environment otherwise known as controlled atmosphere packaging is synonymous to reduction in O_2 and increase in CO_2, coupled with continuous checking and active regulation of the composition of gas. A modified atmosphere, conversely, has no active regulation of the gas composition, but when compared with ambient air, possesses different gas composition [16].

- **Storage under controlled atmosphere (CA):**Commercial storage using this technique was first applied for the storage of apples in 10 kPa CO_2 and ambient O_2 in England in 1929 [17]. This involves continuous maintenance of given specific gas composition of the surrounding atmosphere of the fresh produce by continuously compensating for the changes that occur because of the respiratory activities of the fresh produce. For apples, O_2 concentrations between 3 and 4kPa is maintained. Ultra-low oxygen (ULO) storage is an analogue of CA which use lower concentrations of O_2. The advised concentrations of oxygen (O_2) for lots of cultivars of apple are between 1 and 2 kPa. This made it possible to keep some apples in storage for more than a year. in CA storage [7].

- **Modified atmosphere storage (MAS):**MA is differentiated from CA as the gas composition is not monitored and adjusted actively.Modified storage process involves flushing the package of the fresh produce with ambient air or CO_2/O_2 gas mixture prior to closing of the package. The idea is for the respiratory activity of fresh produce to deplete O_2 content in the package and the CO_2 composition to increase to attain intended gas composition in the packaging's head space. The equilibrium between the metabolic activities of the wrapped commodity and barrier qualities of the films used in packing will result to a condition of equilibrium concentration within the package, otherwise known as ***equilibrium-modified atmosphere***(EMA) storage.

The MAP -modified atmosphere packaging as a system in equilibrium is often created and fabricated in a manner that the concentrations of gases at equilibrium mimic the optimal gas concentrations found in laboratory tests in which goods are kept in various stable gas environments. To generate meaningful insight into the respiratory qualities of fresh produce and how they are influenced by oxygen (O_2) and carbon dioxide (CO_2), an appropriate use for modified atmosphere packaging (MAP) is necessary [16].

Other hybrid of MA includes but not limited to active packaging and modified humidity packaging (MHP). In *active packaging*, special compounds are incorporated to absorb a few of the package's gases (oxygen, carbon dioxide and ethylene) or the specific compounds added emit gases into the package surrounding head space. *Modified humidity packaging*, commonlyabbreviated as MHP is used to control humidity of the package. MHP achieves optimal humidity level for the product but does not provide control of O_2 and CO_2 concentration of the food environment. The major function of MHP is to prevent dehydration and microbial spoilage of the product [16].

4. Transpiration

Thiscan be describedas a phenomenon of passage of water through tissues of a plant and the subsequent vapourisation of that water from aerial parts including leaves, stems, and flowers. It is a mass transfer activity, from the tissue of agricultural produce. Although water is vital for plant, only a tiny portion of it is used for growth and metabolism by the roots. Transpiration and guttation account for the remaining 97- 99.5 percent of loss [18]. The water levels of fresh commodities vary from 80% to 95% and each product has it unique and peculiar water content. In fruits and vegetable, flow of water and gases is established through a continuous intercellular space [19]. After harvest, fresh produce continues to undergo processes of transpiration, and if not controlled will lead to dehydration and wilting. In transpiration, due to variance in water vapour pressure, water vapourise off the surface of fresh commodities and disperses into the atmosphere. The resultant effects of transpiration (water loss) on fruits and vegetables include shrinkages, wilting, loss of firmness and crispiness. Consequently, the mass of the produce, appearance, texture, and flavour are impacted. The freshness of fruits and vegetable are established to be lost after about 3 to 10% loss of mass [18].

The process of transpiration is explained by Fick’s law. Ficks law posits that the movement rate of a gas through a material (flux), (for instance, the diffusion of water vapour into and out of fruit or vegetable) is directly proportionate to its difference in partial pressure and in reverse relates to the resistance [16].

$$\text{Flux} = \frac{P_s - P_a}{r} \qquad (4)$$

where the term $(Ps - Pa)$ is the pressure gradient i.e.,r is the resistance to vapour transport through this barrier, measured in s m^{-1}, and Ps and Pa are the vapour pressures at the surface of the commodity where evaporation occurs and surrounding air, respectively. From equation 2.4, it can be inferred that the force driving process of moisture loss is the pressure gradient between the plant tissue and the environmental gas space. Transpiration occurs in a bid to reduce to zero the pressure gradient between the environment and internal tissues of fresh produce. Most often than not, especially in the tropics and subtropics, there is a wide differential between these two pressures leading to loss of water to the surrounding by the fresh produce. The R.H of the environment determines migration of water out of or otherwise its ingress into fresh fruits and vegetables. High relative humidity favors moisture condensing on the surface of the produce leading to proliferation of spoilage fungi and bacteria. In contrast, low relative humidity of the surroundings or packaging system of the fresh produce accelerates moisture loss through transpiration process and set in of quality degradation, shrinking and wilting.

4.1 Factors affecting transpiration (water loss).

The following factors affects the rate of transpiration.

- **Water vapour pressure deficit:** transpiration is driven by pressure gradient. The phenomenon of transpiration can only occur when there is wvp differential involving the inside of the fresh commodity and the environment (a scenario of higher water pressure in the interior of the produce). While the vapour pressure of the surrounding environment of fresh commodity is affected by temperature and humidity levels, the interior vapour pressure of fresh commodity is only reliant on the temperature of the commodity [16]. The transpiration rate is represented in as a relationship between coefficient of transpiration, mass, and vapour pressure differential of a particular produce [20].

Transpiration rate (TR) = K X M X ΔP ……………………………….……..….. (5)

The coefficient of transpiration (transpiration coefficient) is the reciprocal of the resistance (r) and the variance in internal vapour pressure (ΔP) at the commodity's surface subtracted from the external vapour pressure. Most often than not, relative humidity is used to express the WVP deficit. The evaporation is thus exactly related to the discrepancy between the R.H in the air and at point of saturation, that is, at 100 percent, under the premise that 100 percent relative humidity is equivalent to the equilibrium wvp. At higher humidity, an alteration in relative humidity results to higher change in evaporation as against lower relative humidity. For instance, evaporation at 5% change in relative humidity is dependent on whether the reference relative humidity is high or low. Evaporation increases by 250 percent when the relative humidity rises from 98 to 93 percent, but only by 33 percent when the relative humidity rises from 85 to 80 percent [21].

- **Temperature:**temperature affects the rate of transpiration by altering the water gas pressure (WVP) at which the interior of a fresh good and its surroundings are in balance. If the fresh fruit and vegetable temperature is beyond that of the storage air, the vapour pressure equilibrium is raised remarkedly [21]. On the other hand, if the variance between the air and temperature of the product is satisfactorily wide, (for instance for the period of postharvest initial cooling), the WVP of the surrounding air becomes very minute when compared to the WVP equipoise concentration. In this instance, instead of cooling the produce with humidified air to reduce loss of moisture, the balanced water vapour pressure (WVP) and therefore the temperature is reduced [21]. For the same reason, when the storage room of fruits and/or vegetables have non-uniform temperatures, some parts would be subjected to high-water vapour deficit. This leads to different rates of moisture loss by the fruits and/or vegetable, as well as occurrence of condensation [16]. The temperature of the air is very essential in the instance that the water composition of the air is conveyed as R.H. For instance, the air's WVP deficit is 43 percent greater at 5 ^{o}C and 95 percent relative humidity than it is at 0^{o}C with the same relative humidity [21].
- **Storage environment:**apart from relative humidity, heat of respiration and velocity of air, moisture loss also greatly varies dependently on how far the air is from the bulk of the product and bulk density [22]. DeEll*et al*. [16] reported the following observations from models and experiments.

(a) A rise in air velocity (for instance, cooling using air under applied force) reduces the hotness of the produce. The reduction in hotness gradient reduces the rate of transpiration. The exception to this rule is when air first contacts the fresh commodity.

(b) With exception to wherever the air flow move into the load, fruits and vegetables with high transpiration coefficient are affected minimally or so little by initial humidity. In this situation, low relative humidity has a devastating impact.

(c) Also, for produce with an elevated transpiration coefficient, the beginning RH has minimal impact on the transpiration in most of the fruit/vegetable where the level is approaching saturation.

(d) R.H is heavily influenced by factors of moisture loss but is unrelated to the velocity of the air, initial R.H and respiration heat.

(e) Notably, increase in respiration heat markedly leads to an increase in the moisture loss differential or gradient. Leakage of heat into storage rooms of fresh produce will have analogous effect.

- **Product respiration:**notably, CO_2, heat,and water are created during breathing. Both water and heat produced during respiration directly impacts how quickly water is lost (transpiration). While the water generated during respiration is retained inside the tissues of the fruit or vegetable, the heat produces is emitted to the environment by transpiration and direct heat transfer [23]. The warmth produced during breathing increases the hotness of the product and in turn results in an increase in transpiration by creating vapour pressure deficit [16].

- **Size, shape, and surface of a produce:**large fresh produce tends to transpire more on a basis of mass (loss per mass) than smaller fruits due to a higher surface area (surface/volume) [19]. The geometry of the commodity also impacts the rate of transpiration, as higher surface-to-volume ratio in long and tiny fruits results in faster shriveling. Also, the surface morphology of the produce affects transpiration rate. Fruits and vegetables lose water through epidermal hairs, stem scars, lenticels, stomata, cracks in the cuticles, and wounds, but are minimised in the presence of waxy surface coatings.

- **Maturity and ripening:**The transpiration rate in fruitsis seen to be constant regardless of the maturity level. This is at variance with the behaviour of other fruits of the tropics such as pawpaw, which shows a rise in transpiration at maturity, with consequent changes in the colour and the incipient of the ripening (climacteric). Also, the transpiration rate of bananas and mangoes is seen to be steady and slow at green and unripe stage. This is preceded with a fast increase in transpiration rate at the initial stage of the process of ripening. Then, fruits that are ripe as well as overripe exhibit a consistent, but often gradual, upward trend [16]. The increased in transpiration observed for some commodities during ripening has been attributed to increase in cell wall permeability that associated ripening process.

4.2 Control of transpiration

Notably, vapour pressure deficit is the driving force for transpiration to take place and therefore, minimizing or when possible, eliminating the WVP differential in respect of the interior of fresh produce and the contiguous air will reduce the speed of transpiration. Cutting down the water vapour pressure (WVP) difference (ΔP) is accomplished by lowering the temperature of the atmosphere around the food. Also lowering of WVP differential can be achieved by raising the storage environment's relative humidity. The quantity of water that must evaporate from the product prior when the atmospheric air becomes saturated with vapour from moisture is decreased by reducing temperature and/or elevating R.H of the environment [16]. As earlier noted, water vapour of air surrounding a commodity is a function of the humidity and therefore humidity is manipulated to produce vapour pressure close to the interior of the produce. Very high relative humidities in the range of 95–99% are prevalently needed for products that are succulent in nature, while substantially lower humidity at about 60–70% are required for produce with less moisture like tubers, corms, and cured roots (Kays, 1991). Notably, temperature affects relative humidity which will, in turn, affects the vapour pressure differential. A rise in the ambient temperature results in the vaporisation of moisture and cause a decrease in relative humidity and accelerates water loss. The moisture exchange in storage is clearly impacted by the following temperature variables:

(a) the temperature as it is.

(b) the temperature difference of the product when compared with the environment; and

(c) changes in storage temperature.

The interplay of these factors is presented in psychrometric charts shown in Figure 1. As evidenced by the psychrometric chart that a decline in temperature has a negative impact on how much water the air can contain. Consequently, a decrease in the temperature of the surrounding air at a given R.H will result in a decline in the wvp differential between commodities and their environment. This will in turn lead to a reduction in transpiration. Therefore, it is very essential to cool fresh commodity rapidly to reduce the loss of water.

The various methods employed to reduce the rate of transpiration and thereby enhance maintenance quality and reduce economic loss of fresh produce are discussed.

- **Storage conditions**:storage of fresh commodities in a high relative humidity environment ensures moisture saturation and thereby decreases transpiration. Raising the ambient environment's relative humidity is achieved by increasing the cooling surface area, though this will not be able to achieve 90% relative humidity. Other methods are employed such as direct humidification and refrigerated air injection. Limiting the flow of air around commodity stored cold environment can, consequently, reduce the rate of transpiration. Practically, reduction of transpiration of precooled fresh produce can be achieved by gradual decrease of the amount of air movement. This in turn can be achieved by reducing the duration the fans are operated, or/and by running them at lower speeds [24].

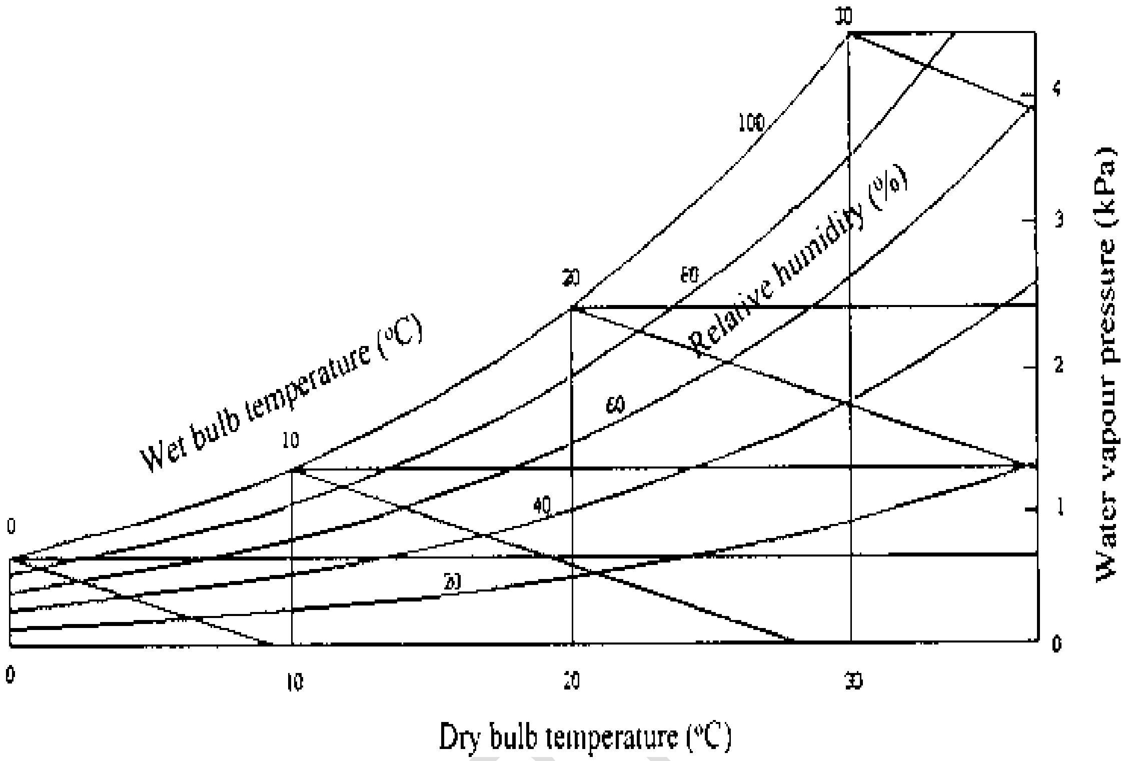

Figure 1: Condensed psychrometric chart

Source: DeEll*et al*. [16]

- **Packaging:** transpiration in fresh produce have been successfully reduced markedly by using appropriate packaging materials. Packaging materials functions as a barrier to the transpiration in fresh produce. The simplest techniques of using packaging to reduce transpiration are to enclose the product in cartons, boxes, or bags, or to enclose packs of fresh produce by using tarpaulins [24]. Also, packing fruits closely together reduces the surface area for air flow and thereby reduce transpiration. The ability of a packaging material to reduce water loss is dependent on its permeability to water. The lower the barrier characteristics of the films used for packing, the higher the protection of fruits and vegetables against water loss. Packaging materials made of polyethylene possess low vapour permeability when compared to paper and fibreboards packages. This inherent vapour barrier property of polyethene materials made it more suitable for reducing moisture loss of fresh produce. When storing, transporting, and selling food, it is simple to guarantee high relative humidity by using films made from plastic, bags, wraps, liners, or bulk-box coverings [25]. Such films and coatings, increased water vapour transmission resistance will result in a micro atmosphere with a greater R.H than the surrounding air. Most packaging films must typically be perforated or not secured tightly since they are not sufficiently permeable to be utilised as sealed packaging. Because of the water that condenses inside the container and the high humidity, packaging with films may also speed up decomposition [16].

Also, the application of extreme thin plastic packs has been found to reduce shriveling, loss of mass firmness and decay [26]. The utilisation of thin plastic packaging involves sealing of the fresh commodities in plastic films and passing them through shrinking the film in a hot air tunnel [25]. Modified Humidity Packaging (MHP) had been designed to reduce moisture loss as well as avoid condensation in fresh produce. Antifog layers are incorporated into films or packages to counter the effect of condensation. This prevents droplets of water on the produce,instead continuous watery layer is deposited on the surface of the films/packages. Antifog layers on films/ packages allows for transparent view of the stored produce and prevent coming together of water at the bottom part of the packages. Transpiration being the most prevalent root cause of deterioration quality, application of modified atmosphere packaging can effectively reduce loss of quality [16].

- **Surface coatings:**in the olden days, fruits such as apple are coated with waxes to reduce water loss. The idea behind wax coating is to decrease the water resistance characteristics of the fruit coverings and thereby ensure reduction in transpiration. In addition to the intent to minimise transpiration, application of coatings on fruits was also meant to enhance gloss and appeal. Use of coatings to minimise transpiration in commodities, also achieves reduction in loss of mass which translates to unaffected economic sale quantity of the commodity. Mass loss and incidences of discoloration of stems and pitting of surface in cherries during storage was decreased by coatings [27]. Some of the characteristics of a good coating includes nontoxic to humans, stability in formulation, good permeability properties, rapid drying, high gloss, strong attachment to the fruit for the duration of the storage and affordability [28]. Carnauba, shellac, cellulose, carrageenan, and resin coatings offers distinct levels of resistance to gas exchange and permeability is influenced by the makeup and surface coatings thickness.

5. Ethylene

In trace levels of less than 0.1 µL L^{-1}, ethylene (C_2H_4), the most basic olefin, may significantly trigger the respiration and senescence process in a variety of harvested commodities [29]. Natural plant hormone ethylene may either have a good (degreening and ripening) or negative (damaging) effect on fruits that have been harvested (abbreviated storage and softening). The amount of ethylene impacts is influenced by temperature, exposure period, and ethylene concentration. The effects of ethylene build up over time throughout the fruit's postharvest life [30]. The singular well-known gaseous plant growth regulator that is present at normal ambient temperature is ethylene. It can be produced biologically and non-biologically and has many different impacts on germination, growth, flowering, fruiting, ripening, abscission, senescence, and dormancy at a very low concentration. Ethylene is most often called the 'ripening gas.' This is because ethylene promotes ripening and senescence through a series of biochemical catalysis. In addition to the ripening, there are other effects of ethylene on fresh produce after harvest. This includes decrease in chlorophyll, stimulation or subdual of potato sprout growth, and stimulation or subdual of resistance to diseases. Depending on how the product is to be used, the actions of ethylene can be detrimental or desirable. If the storage operator is unaware of the impacts of ethylene gas and/or does not have an ethylene detector, leakage, and impact of ethylene gas in a fresh commodity storage environment may not be noticed [16].

5.1 Ethylene production

Both biological and non-biologic methods can be used to manufacture ethylene.

- **Biological production:**Production of ethene bacteria, fungi, animals, flowering, and non-flowering plants has been reported by many researchers. Ethylene production from methionine through ACC pathway represents the major source of its production in flowering plants. Nonflowering plants produce ethylene when they are damaged or stressed using unknown pathways as they do not possess ACC oxidase found flowering plants (John, 2006).

- **Non-biological ethylene production:**ethylene gas can be generated from organic materials non-biologically by incomplete combustion. This explains the reason wood ash is applied traditionally to bananas, plantain, and other fruits to quicken the ripening process. Incomplete combustion of woods and leaves produces ethylene, the first member of the alkyne homologous serious of a group of organic compounds. Prior to the identification of ethylene, stored fruits and vegetable are ripened by exposure to smoke, kerosene heater, illuminating gas, and burning of incense. This practice elicits the same responses as ethylene unknown to earlier farmers that the ethylene gas is produced, and it is responsible for the changes observed [31].

5.2 Effects of ethylene on respiration and fruit ripening

Vegetables have one respiration pattern of decreasing rate from immature to aging stage. So, respiration rate is highest at immature stage and lowest as the tail end of aging. This phenomenon is unlike fruits with two different respirational patterns, termed climacteric, and non-climacteric. Non-climacteric fruits have the same pattern as vegetables exhibiting decrease in respiration down the life span. On the other hand, climacteric fruits experience a surge or rise in respiration rate immediately after maturity and just before ripening and drop after ripening during senescence and final death as shown in Figure 2. With this distinction in the respiratory model of climacteric and non-climacteric fruits, they tend to behave differently when exposed to ethylene. Climacteric fruits have shown that a rise in endogenous ethylene generation coincides with the rise in respiration (climacteric) and subsequent ripening and senescence. Ethylene gas applied externally to climacteric fruits can also generate the same effects and responses as its endogenous counterpart,based on the type of fruit and its maturity level.Conversely, the rate of respiration and senescence is accelerated when external ethylene is applied to non-climacteric fruits and vegetables. Also, both rates of respiration and senescence decline if ethylene is removed. The response from the application of exogenous ethylene gas on non-climateric fruits compared well with a single respiration peak in climacteric fruits [16][33]. Table 2.3 presented the grouping of different fruits into two, which are the climaterics and the non-climaterics.

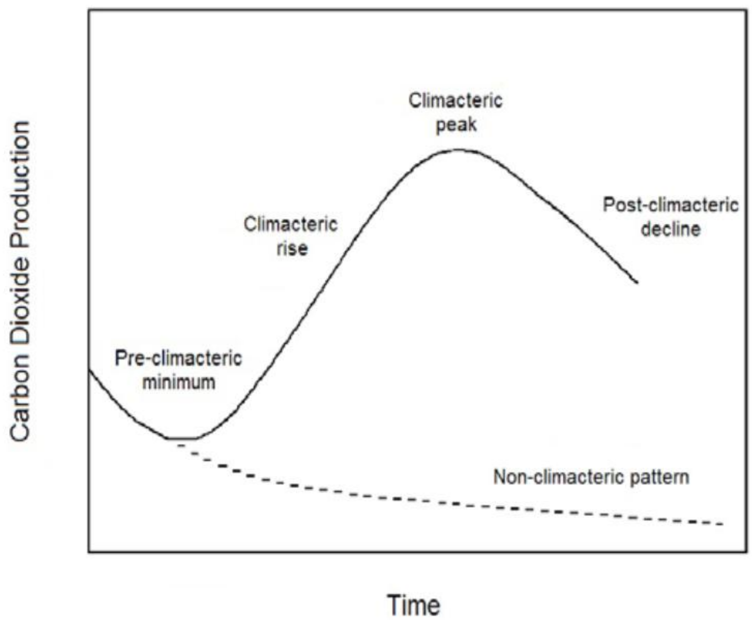

Figure 2: The pattern of respiration during repining by climacterics fruits

Source: [8][32]

6. Conclusion

The physiological processes affecting postharvest quality of fruits and vegetables are multifaceted and dynamic, influenced by a myriad of factors including metabolic pathways, environmental conditions, and handling techniques. Through this review, we have delved into the intricate mechanisms underlying fruit and vegetable deterioration postharvest, highlighting the pivotal roles of respiration, ethylene production, enzymatic activity, and water loss.

Furthermore, we have explored the significance of pre-harvest factors such as cultivar selection, cultural practices, and crop management in determining postharvest quality. Additionally, advancements in postharvest technologies, including modified atmosphere packaging, controlled atmosphere storage, and edible coatings, have demonstrated promising outcomes in preserving the freshness and nutritional content of produce.

While significant progress has been made in understanding and mitigating postharvest losses, there remain challenges and opportunities for further research and innovation. Future endeavors should focus on developing sustainable and cost-effective strategies to prolong shelf life, minimize waste, and enhance the nutritional value of fruits and vegetables. Collaboration among researchers, growers, industry stakeholders, and policymakers is essential to address these issues comprehensively and ensure a resilient and efficient postharvest supply chain. By leveraging interdisciplinary approaches and harnessing technological advancements, we can strive towards a future where postharvest losses are minimized, and consumers worldwide have access to high-quality, nutritious fruits and vegetables.

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