International Journal of Environment and Climate Change

Volume 13, Issue 10, Page 3548-3558, 2023; Article no.IJECC.106086
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

A Comprehensive Review on Nature and Causes of Deterioration in Fruits and Vegetables

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2023/v13i103025

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/106086

Review Article

Received: 04/07/2023
Accepted: 09/09/2023
Published: 18/09/2023

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ABSTRACT

The issue of post-harvest deterioration in fruits and vegetables constitutes a critical concern, especially given the rising global food security challenges. The aim of this review article is to present a comprehensive examination of the diverse facets contributing to the deterioration of these valuable food resources, ranging from biological and environmental factors to economic implications and current preservation methods. One area of focus involves scrutinizing the gaps in the current body of knowledge, particularly the intricate molecular mechanisms governing enzymatic activity and microbial spoilage. Recent developments in technology also present intriguing possibilities for future research. Artificial Intelligence (AI) offers transformative potential in monitoring the quality of stored produce by predicting the onset of spoilage using complex algorithms. This work also delves into the prospects of employing the Internet of Things (IoT) for real-time assessment and control of storage conditions, which could revolutionize supply chain management and significantly minimize deterioration during transport. Another exciting avenue lies in the utilization of novel packaging materials especially those which are biodegradable and may be imbued with natural preservatives, a move that aligns well with global sustainability goals. Any such technological advancements must be scrutinized in the context of existing food safety standards and regulations, both at the national and international levels. These standards govern everything from permissible microbial activity levels to waste management, and are dictated by organizations such as the FDA and EFSA, as well as international frameworks like the Codex Alimentarius.

Keywords: Deterioration; sustainability; artificial-intelligence; packaging; fruits and vegetables.

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1. INTRODUCTION

Fruits and vegetables are cornerstones of a balanced diet, providing essential nutrients like vitamins, minerals, fiber, and antioxidants [1]. They play a significant role in preventing chronic diseases such as heart diseases, diabetes, and cancer [2]. Consumption of fruits and vegetables is also associated with lower rates of obesity and improved gut health. The World Health Organization recommends a minimum of 400 grams of fruits and vegetables per day for preventing chronic diseases [3]. Despite their importance in human health, a significant portion of fruits and vegetables deteriorate before reaching consumers, leading to waste and economic losses [4]. According to estimates by the Food and Agriculture Organization, roughly one-third of all produced food is wasted globally, and fruits and vegetables have the highest wastage rates of any food type. The deterioration is often due to factors such as enzymatic breakdown, microbial spoilage, or poor storage conditions [5]. The primary objective of this review is to provide a comprehensive understanding of the nature and causes of deterioration in fruits and vegetables post-harvest. By exploring the biological, environmental, and chemical factors contributing to spoilage, this review aims to highlight potential solutions and areas for future research [6]. The scope of this review covers a broad range of topics related to the deterioration of fruits and vegetables, including but not limited to Biological and environmental factors affecting quality., Chemical changes occurring during spoilage, Economic implications, Current and emerging technologies for preserving quality, Regulatory and policy considerations [7].

1.1 Historical Background

The concept of post-harvest deterioration is not new and can be traced back to the early 19th century. The dawn of agricultural sciences recognized that harvested produce, specifically fruits and vegetables, were susceptible to spoilage [8]. The seminal work on the subject came from Charles Wilson in 1890, whose paper in the *Journal of Agricultural Science* was among the first to systematically study the phenomenon. Wilson observed that microbial activity was a leading cause of spoilage, leading to the idea of canning and basic preservation techniques [9]. While these early studies were largely observational and lacked the empirical rigor of modern science, they set the foundation for the more advanced research that followed. These laid down the initial roadmaps for studying complex biochemical processes involved in deterioration like enzymatic actions and oxidative stress [10]. In the early 20th century, as industrialization rapidly advanced, new methods to prolong the shelf life of produce were developed. The simple barn storage of the 19th

century evolved into more controlled environments. The concept of "cold storage," for instance, gained popularity after seminal research by Kauba and Vance [11]. demonstrating how low temperatures reduced metabolic rates in produce. This breakthrough led to the large-scale use of cold storage units by the mid-2[0th] century [12]. A significant milestone was the introduction of Controlled Atmosphere (CA) storage in the 1960s. This technology allowed for the manipulation of oxygen and carbon dioxide levels in storage units, thereby significantly delaying ripening and reducing spoilage [13]. Since then, various other techniques like vacuum storage and the use of preservatives have been employed. Each advancement in storage technology came as a response to increasing demand for longer shelf life and the global distribution of produce [14]. In the last two decades, technology has played an ever-increasing role in combating post-harvest deterioration. The advent of sensor technology, for example, has enabled real-time monitoring of storage conditions. Research by Floros et al. [15] demonstrated how RFID sensors could be used to track temperature and humidity changes during transportation, thereby signaling any adverse conditions that could lead to spoilage. The application of nanotechnology in packaging is another game-changing technological advancement. Coatings made from nanoparticles have been shown to have antimicrobial properties, thereby increasing the longevity of produce [16]. Perhaps the most revolutionary technology has been the use of artificial intelligence (AI) and machine learning algorithms for predictive analytics. Modern storage units equipped with AI can adjust the storage conditions in real-time based on predictive algorithms, thereby significantly reducing spoilage [17]. Each technological advancement has not only improved the storage and longevity of fruits and vegetables but has also economic impacts. The advancements have opened new markets, reduced wastage, and, most importantly, contributed to food security [18].

2. FACTORS INFLUENCING DETERIORATION

2.1 Biological Factors

Factors influencing the deterioration of fruits and vegetables are multifaceted, particularly within the realm of biological factors (Table 1). Enzymatic browning serves as a prominent form of spoilage, often mitigated by enzyme inhibitors that can slow down enzymatic activities [20]. Microbial agents, including bacteria, yeasts, and molds, are primary contributors to spoilage, with certain fruits and vegetables being particularly susceptible [21]. Chemical methods like the use of preservatives and pH adjustments are employed to control microbial growth [22]. Diseases such as blight and fruit rot are other common challenges, often managed through the application of fungicides and other chemical treatments [23]. Additionally, the inherent physiology of specific fruits and vegetables, like berries, naturally lends to shorter shelf-lives, although genetic modification offers avenues for improvement [24].

2.2 Environmental Factors

Environmental factors play a critical role in the deterioration of fruits and vegetables, each with distinct mechanisms of action. Low temperatures are known to retard metabolic activities that contribute to spoilage, a principle that is harnessed in Controlled Atmosphere (CA) storage to prolong the freshness of produce [25]. Humidity, too, influences deterioration; low levels can cause desiccation, while high humidity fosters microbial growth, thus necessitating technologies like humidity-controlled compartments for optimal storage [26]. Light exposure is another significant factor, as it can accelerate enzymatic activities that lead to spoilage; this concern is mitigated by using specific packaging materials designed to limit exposure to light [27].

2.3 Physical Factors

Physical factors also significantly contribute to the deterioration of fruits and vegetables. Mechanical damage, such as bruising, exposes the inner parts of produce to oxidation and microbial invasion, necessitating the implementation of technologies and practices to minimize such damage [28]. In terms of packaging, various methods like vacuum sealing, plastic wraps, and the use of nanotechnology have been effective in extending shelf-life [29]. Additionally, transportation-related stresses including vibrations and temperature fluctuations have been identified as influential factors affecting the quality and longevity of produce during transit [30].

Table 1. Biological factors influencing the deterioration of fruits and vegetables

Specific Factor	Description
Enzymatic Reactions	Natural enzymes in the fruit can cause over-ripening or spoilage.
Insect Infestation	Insects can damage the exterior, leading to faster decay and compromised quality.
Pathogen Infection	Diseases caused by viruses, bacteria, or fungi can lead to rot and spoilage.
Respiration Rate	The speed at which a fruit "breathes" can affect its shelf life.
Ethylene Sensitivity	Some fruits emit ethylene gas, which can accelerate the ripening process.
Bruising and Physical Injury	Any physical damage can lead to faster deterioration due to microbial growth.

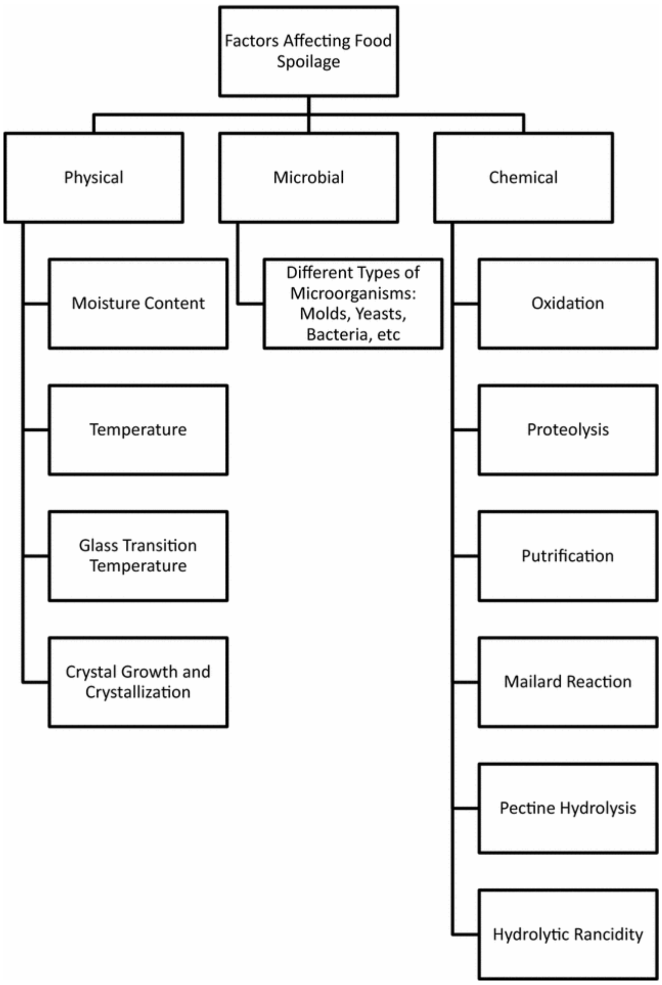

Image 1. Key physical, microbial, and chemical factors affecting food spoilage [19]

3. CHEMICAL CHANGES DURING DETERIORATION

3.1 Change in Nutritional Value

Changes in nutritional value are pivotal aspects of fruit and vegetable deterioration. Water-soluble vitamins, notably vitamin C, are highly susceptible to degradation over time, exacerbated by conditions of heat and light, which also adversely impact fat-soluble vitamins such as A and D [31]. Methods like controlled atmosphere storage have been explored to minimize these losses [32]. In the context of minerals, practices like washing and storage can lead to the leaching of essential elements such as potassium and calcium, while factors like acidity and moisture levels can further influence mineral stability [33]. The consequences of such losses extend to the overall nutritional quality of the produce, highlighting the importance of effective preservation techniques [34].

3.2 Flavor and Aroma Compounds

Flavor and aroma compounds in fruits and vegetables are critically influenced by various elements, including volatile components and changes in sugar and acid contents [35]. Volatile oils are primary contributors to the distinctive flavors and aromas of produce, and their breakdown, often facilitated by enzymes, has a direct impact on consumer acceptability and marketability [36]. Shifts in sugar and acid levels where sugar content may diminish while acidity can escalate alter the flavor profiles of the produce significantly [37]. Such changes are closely tied to storage conditions and have a considerable impact on taste and, consequently, consumer preferences [38].

3.3 Color and Texture Modifications

Color and texture modifications in fruits and vegetables significantly influence their marketability and consumer appeal. The breakdown of pigments like chlorophyll and carotenoids occurs through complex chemical processes, with oxidation playing a key role in this degradation [39]. These changes have direct implications for the visual appeal of the produce [40]. Additionally, loss of cell integrity and structural rigidity contributes to changes in firmness, which are often accelerated by enzymatic activities [41]. Such alterations in texture have a considerable impact not only on consumer preferences but also on the transportability and shelf life of fruits and vegetables [42].

3.4 Economic Impact

The economic impact of fruit and vegetable deterioration is multi-faceted and has wide-ranging implications for various stakeholders, from producers to consumers and even nations. At the agricultural level, spoilage leads to substantial financial losses, exacerbating the costs of waste disposal and failed storage techniques [43]. These impacts disproportionately affect small farmers compared to industrial operations [44]. For consumers, deterioration escalates food prices and incurs hidden costs, including health risks from spoiled produce and waste management expenditures [45]. Additionally, consumer trust in agricultural products can erode, adding a psychological cost [46]. On the international stage, quality standards create import and export challenges, impacting countries that rely heavily on fruit and vegetable exports [47]. The necessity of complying with international regulations also adds to the economic burden [48].

3.5 Current and Emerging Technologies to Mitigate Deterioration

Advancements in technology are making strides to counteract the deterioration of fruits and vegetables effectively. Controlled atmosphere storage has shown to delay spoilage by manipulating levels of oxygen, carbon dioxide, and humidity, and sensor technologies for real-time monitoring are further optimizing these storage environments [49]. Edible coatings, particularly those derived from natural polymers like chitosan, are gaining traction for their protective qualities. These coatings are increasingly being fortified with antioxidants and antimicrobials, although consumer acceptance and regulatory hurdles still need to be fully addressed [50]. Post-harvest treatments such as irradiation are effective in controlling spoilage and extending shelf life, but their safety and environmental impacts remain areas of research [51]. Heat treatment methods like blanching and novel techniques like ohmic heating are also utilized to suppress enzymatic activities that lead to spoilage [52]. Natural preservatives, such as essential oils from thyme and oregano, as well as antimicrobial peptides, have shown promise but face challenges in scalability and safety considerations [53]. Alao [2] reported that the most suitable condition for fresh fruits and vegetables in storage is the lowest temperature, which does not cause chilling injury to the fresh produce. Any variation from the desired condition is detrimental. Relative humidity of the store rooms also has a considerable bearing on the keeping quality of the fresh produce. Therefore, control of moisture in air is very difficult [12]. The rate of respiration has direct correlation with temperature, as the temperature is high more will be the rate of respiration and multiplication of decay organisms. But it should be noted that the temperature and relative humidity requirements differ for different fruits and vegetables. Therefore, the maximum cold storage conditions for fruits and vegetables are given separately in Tables 2 & 3 [54].

Table 2. Recommended storage temperature and relative humidity for different fruits [54]

Sl. No.	Name of the fruit	Storage temp. (%)	Relative humidity (%)	Storage period (weeks)
1	Pineapple	8-10	85-90	1-2
2	Pomegranate	0-1.66	85-90	16-17
3	Guava	8.30-10.00	80-85	4
4	Mango	7.20-8.80	85-90	4-7
5	Emblica (Amla)	0-1.66	85-90	7-8
6	Grapes	0-1.66	80-85	6-8
7	Fig			
	(a) Fresh fruits	0-1.66	80-90	4
	(b) Dry fruits	0-1.66	65-70	52
8	Cashewnut	0-1.66	85-90	4-5
9	Jackfruit	11.10-12.70	85-90	6
10	Banana			
	(a) For ripening	15.50-21.00	80-85	1-2
	(b) Ripened fruit	11.10-12.70	85-90	3
11	Date palm			
	(a) Fresh fruits	7.20-8.80	85-90	2
	(b) Dry fruits	0-1.66	65-70	40-52
12	Grapefruits	7.20-8.80	85-90	12
13	Rough lime	5.50-7.20	85-90	13-17
14	Sapota (cheeku)	1.66-3.30	85-90	6-8
15	Cherry	0-1.66	85-90	2
16	Pear	0-1	85-90	13-26
17	Papaya	8.30-10.00	80-85	1-2
18	Passion fruit	5.50-7.20	80-85	4-5
19	Malta			
	(a) Malta common	3.90-5.50	85-90	17
	(b) Blood red	2.20-3.90	85-90	17
	(c) Mosambi	5.50-7.20	85-90	21
	(d) Valentia late	3.90-5.50	85-90	17
	(e) Sathgudi	5.50-7.20	85-90	17
20	Lime	8.30-10.00	85-90	6-8
21	Litchi	0-1.66	85-90	10
22	Lemon	7.20-8.80	85-90	8-12
23	Strawberry	0-1.66	85-90	5-6
24	Santara	3.90-5.50	85-90	10-14
25	Apple	0-1.66	85-90	17-34
26	Plum	0-1.66	85-90	2-4
27	Peach	0-1.66	85-90	2
28	Bael	8-9	85-90	10-12

3.6 Regulatory and Policy Considerations

Regulatory and policy considerations in the realm of food deterioration are multifaceted, encompassing food safety standards, sustainability initiatives, and complex legal frameworks. Existing food safety protocols like the Hazard Analysis and Critical Control Points (HACCP) set guidelines for preventing spoilage, and national bodies such as the FDA and EFSA enforce stringent criteria for microbial activity in food [55]. Concurrently, sustainability and waste management are increasingly being embedded into regulations, emphasizing eco-friendly post-harvest handling and reduction of food waste [56]. Third-party certifications like Fair Trade also contribute to these sustainable practices [57]. On an international scale, frameworks like the Codex Alimentarius serve as the base for national regulations, but complexities arise in harmonizing these standards, particularly for key global players such as the United States, European Union, and China [58].

Table 3. Recommended storage temperature and relative humidity for different vegetables [54]

Sl. No.	Name of vegetable	Temperature (ºC)	Relative humidity (%)	Storage life (weeks)
1	Asparagus	0-0	95	3-5
2	Brinjal	10.0-11.10	92	2-3
3	Dolichos lablab (pod)	0.0-1.7	90	3
4	Beet (toppled)	0.0-1.7	90-95	8-14
5	Beet (bunched)	0.0	90	1.5
6	Bitter gourd	0.6-1.7	85-90	4
7	Cabbage (early)	0.0-1.7	92-95	4-6
8	Cabbage (late)	0.0-1.7	92-95	12
9	Carrot (toppled)	0.0	95	20-24
10	Cauliflower	0.0-1.7	85-95	7
11	Celery	0.6-0.0	92-95	8
12	Colocasia	11.1-12.8	85-90	21
13	Coriander	0.0-1.7	90	5
14	Cucumber	10-11.7	92	2
15	Garlic	0.0	65	28-36
16	Ginger	7.2-10.0	75	16-24
17	Lettuce (head)	0.0	90-95	3
18	Lettuce (leaf)	0.0	95	1
19	Lima bean (pod)	4.4-7.2	90-95	1.5-2
20	Muskmelon			
	(a) Cantaloupe	1.7-3.3	85-90	1.5
	(b) Honey dew	7.2	85	4.5
21	Okra	8.9	90	2
22	Onion (leaf)	0.0	90-95	2
23	Onion (bulbs)	0.0	70-75	20-24
24	Pea (green)	0.0	88-92	2-3
25	Pepper (ripe)	5.6-7.2	90-95	2
26	Potato (iris)	3.0-4.4	85	34
27	Pumpkin	1.7-11.6	70-75	24-36
28	Radish (topped)	0.0	88-92	3-5
29	Squash (winter)	12.8-15.6	70-75	24-36
30	Sweet potato	10-12.8	80-90	13-20
31	Cassava	0-1.7	85	23
32	Tomato (unripe)	8.9-10.0	85-90	4-5
33	Tomato (ripe)	7.2	90	1
34	Turnip	0.0	90-95	8-16
35	Watermelon	7.2-15.6	80-90	2

3.7 Future Research Directions

Future research directions in the field of food deterioration and preservation are diverse, ranging from basic science to advanced technologies. There are notable gaps in current knowledge, such as the incomplete understanding of the molecular mechanisms behind enzymatic activity in post-harvest produce and the need for further research on lesser-known spoilage bacteria [59]. Additionally, studies exploring consumer behavior related to novel preservation methods are scarce [60]. On the technological front, advancements in artificial intelligence could revolutionize quality monitoring. Machine learning algorithms could predict spoilage onset by analyzing sensor data, and IoT could be integrated for real-time monitoring of controlled atmospheres [61]. Novel materials for packaging, such as smart packaging that indicates freshness and biodegradable materials infused with natural preservatives, offer exciting possibilities but come with their own sets of challenges, including cost, regulations, and consumer acceptance [62].

4. CONCLUSION

In light of emerging challenges and technological advancements, the future research directions in the field of post-harvest deterioration of fruits and vegetables appear multifaceted. Significant gaps persist in our understanding of enzymatic activity and microbial spoilage, providing fertile ground for deeper investigation. The integration of Artificial Intelligence and Internet of Things holds promise for real-time quality monitoring and effective supply chain management. Moreover, the development and adoption of novel, sustainable packaging materials could revolutionize preservation methods. These innovations must navigate regulatory complexities and gain consumer acceptance to make a meaningful impact. The scope for groundbreaking research is expansive, with the potential to significantly mitigate economic losses and enhance food security.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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