MICROGREENS : PIONEERING THE FUTURE OF SUSTAINABLE NUTRITION

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Abstract

Malnutrition possess a severe problem in our society, leading to various chronic disorders. Functional foods have a significant impact on combating malnutrition, and among them microgreens are a beneficial options. Microgreens are immature vegetables that reach a height of 1-3 inches and are harvested between 10-14 days after seeding. They have a high nutrient profile, containing more vitamins, minerals, and bioactive compounds in comparison to their fully developed counterparts. Enriching diet with microgreens contributes to a well-balanced and nutrient-rich diet, and their production requires only limited resources, enhancing food security for the future. Microgreens have a limited shelf life, which hinders their commercial expansion. To preserve their quality and enhance shelf life, several strategies have been put forward. Additional approaches must be developed to maintain the nutritional quality of microgreens. This paper provides an exploration of microgreens, focusing on their nutritional profile, health benefits, production, and strategies to extend their shelf life.

Key words - Malnutrition, Functional foods, Microgreens, Shelf life

1. Introduction

Maintaining a nutritious and balanced diet is crucial for promoting overall well-being and optimal health. Approximately three billion individuals worldwide are unable to afford nutritious diets, with a significant majority residing in Africa and Asia [1]. Chronic diseases, pose a significant risk when accompanied by malnutrition. The prevalence of diet-related NCDs, including, cancer, cardiovascular disease, stroke, hypertension ,obesity and diabetes, is on the rise worldwide. Out of the approximate annual chronic diseases related mortality rate of 40.5 million individuals (accounting for 71% of global deaths), around 32.2 million deaths (80%) were attributed to diabetes, respiratory diseases, cardiovascular diseases, and cancers [2]. The Second Sustainable Development Goal (SDG 2), established by United Nations aims to eliminate hunger and combat all types of malnutrition. By 2030, it strives to ensure that everyone has year-round availability to safe, nutritious, and ample food, emphasizing the importance of food security for all individuals [3].

Fruits and vegetables are known to possess significant nutritional properties making them essential for a well-rounded diet [4]. The implications of climate change on agriculture presents a risk to future food production. The continuous rise in the global population intensifies the demand for food, thereby affecting food security [5]. Agricultural trends are changing due to food diversification, demand for nutritional foods, fresh greens. Microgreens are a prime example of functional foods that offer various health benefits. Microgreens are immature vegetable that grow up to height of 1-3 inch and harvested between 10-14 days after seedling. It consists of two cotyledonary leaves with one or two true leaves [6].These tiny greens are cultivated from various seeds of legumes, grains, and aromatic plants. They are highly nutritious and offer a wide range of health benefits. The Nutrient Quality Score of microgreens from the Brassicaceae family reveals that these tiny greens are rich in minerals and other dietary nutrients. They have the ability to more effectively improve dietary patterns compared to their fully grown counterparts [7].

The production of microgreens is possible using seeds from a wide variety of crops, vegetables, cereals, and herbs. Table 1 lists the families that are frequently cultivated for microgreens. In particular, the Brassica plants include substances such glucosinolates [8], carotenoids [9,10]; and selenium [11] that may prevent cancer [12]. The hydrolysis derivatives of glucosinolates exhibit antimicrobial traits [13,14]. Plants of the Alliaceae and Lamiaceae families also generate antibacterial chemicals, and other families have also been proven to give a positive impact on human health.These plants are highly valued for their nutritional benefits and are commonly served as toppings in sandwiches, salads, soups, and beverages [15].

Table 1: Families of commonly grown microgreens

Sl.no.	Family	Microgreens
1.	Amaranthaceae	amaranth, beet, quinoa, spinach, buckwheat, chard
2.	Brassicaceae	broccoli, cabbage, cauliflower, Mustard, radish, arugula, watercress, chicory, wild rocket
3.	Cucurbitaceae	melon, squash, cucumber
4.	Poaceae	corn, lemongrass
12.	Leguminosae	alfalfa, Bean, chickpea, clover, green bean, pea, fenugreek, lentil, fava bean
4.	Asteraceae	lettuce, chicory , dandelion, endive, radicchio, tarragon
5.	Boraginaceae	phacelia
8.	Cucurbitaceae	melon, squash, cucumber
9.	Malvaceae	jute mallow
3.	Apiaceae	carrot, cilantro, coriander, chervil, celery, dill, fennel, parsley
11.	Lamiaceae	chia
7.	Convolvulaceae	water convolvulus
13.	Onagraceae	evening primrose
2.	Amaryllidaceae	garlic, leek , onion
14.	Portulacaceae	moss-ross purslane, common purslane

The health benefits of microgreens have been proven in numerous clinical studies. Their unique flavor, exceptional nutritional content, and various health advantages have induced a substantial upsurge in the requirement for this tiny greens. While microgreens offer immense value in terms of nutrition, their short shelf life restricts their availability in mainstream markets. Efforts to extent the marketable quality of microgreens have become a focal point of research to meet the growing demand for this nutritious produce. This chapter review about the nutrition, production and strategies to improve the postharvest quality of microgreens.

2. Microgreens and Nutritional Implications

Microgreens are termed as superfoods, speciality crops and they are classified as functional foods due the exceptional nutritional value and health benefits they provide. These crops are appealed for their unique flavors and vibrant colors, making them popular as culinary ingredients and in salads. They provide adequate nutritional requirements even in small quantities when compared to the corresponding mature vegetable parts [17, 6]. Microgreens are categorized as functional foods owing to abundance of bioactive constituents. Functional foods are the foods that offer potential health benefits beyond mere nutrition [18]. Numerous studies in the literature have reviewed their health benefits, including their potential for suppressing chronic diseases, as well as their proven efficacy in vitro studies [6, 16].

Fig. 1. **Mustard microgreens**

Fig. 2. **Lettuce microgreens**

Microgreens have captured significant attention in the scientific community. Numerous studies have extensively documented the nutritional assessment of commercially available microgreens. In a comprehensive review by [6, 16], the chemical composition of various microgreens is summarized, encompassing vitamins, minerals, pigments, sugar content, and bioactive compounds. Furthermore, the study compares these nutritional aspects with their mature counterparts. The study also investigates their potential health benefits and the underlying mechanisms involved.

Most of the microgreens contain mineral elements and vitamins such as ascorbic acid, tocopherols, phylloquinone, carotenioids etc. The analysis revealed that microgreens with in asteraceae family exhibited higher sugar content, particularly fructose [23]. The total caloric content varied, ranging between 70 kJ -100 kJ per 100 g. Carbohydrate and protein content in lentil and mung bean microgreens were on higher side owing to their higher calorie content (53.43 and 50.08 g 100 g^{-1}) [19]. The nutritional content of microgreens varied based on the selected family and variety.

Microgreens are densely packed with vitamins & minerals. Vitamins A, C, E, K are abundant in most of the microreens [6]. β-Carotene, a class of carotenoids and precursor for vitamin A which is abundant in microgreens. It performs vital physiological functions including vision and development. βcarotene concentration of Cilantro was three times greater than mature cilantro. Additionally, compared to mature red cabbage (0.044 mg/100 g FW), red cabbage microgreens had two sixty times more β carotene (11.5 mg/100 g FW). [20]. The highest levels of β-carotene concentration was shown by fennel and radish with a value of 3.1 to 9.1 mg/100 g [21]. In addition, microgreens were found to contain significant amounts of other carotenoids, including lutein, zeaxanthin, and violaxanthin, at notable levels [6].

Ascorbic acid (AA) content or vitamin C is vital for humans and plays wide varieties of function. The analysis of 25 microgreens demonstrated a diverse range of total ascorbic acid concentrations. Red cabbage and garnet amaranth possessed greater amount of AA concentration (131 mg/100 g) with respect to their fully grown parts [20]. A Comparative analysis revealed that the microgreens exhibited potentially higher levels of ascorbic acid when compared to alternative stages like sprouts and mature vegetables [22].

The study involving 25 varieties of microgreens also displayed considerable variation in phylloquinone/ Vitamin K1 concentrations, with values varying between 0.6 to 4.1 μg/g FW. Likewise Vitamin E concentration in microgreens is substantially higher. It plays a significant role in numerous physiological functions. These functions encompass vital activities such as muscle functioning, immune system enhancement, mitigation of free radical formation etc., Mineral profiling of various microgreens revealed that microgreens are densely packed with minerals likes Ca, K, P, Zn, Mg, Fe, and Cu, Na, Mn [23,7].

Phytochemicals are natural compounds present in plants that have numerous health benefits. They are abundant in microgreens that vary depending on the specific species. It includes flavonoids, phenolic compounds, pigments (carotenoids and chlorophylls), sulphoraphane, glucosinolates etc., these compounds helps to lower the occurrence of diabetes, cardiac illnesses and cancer.

In a study investigating the polyphenol compounds in red cabbage microgreens, it was found that these microgreens exhibited a greater level of polyphenols compared to mature red cabbage [24].The presence of glucosinolates, secondary metabolites produced by microgreens, contributes to health enhancing attributes, which include antioxidant capacity, anti-inflammatory characteristics, and other advantageous effects. They are predominantly present in the Brassicaceae family.

3. Clinical Studies in Microgreens

Microgreens, with their dense concentration of nutrients, have been shown to have health-promoting applications in humans. They have been proven to protect from chronic metabolic diseases, like cardiac illnesses, cancer, diabetes, inflammation, obesity, and iron deficiency in humans.

In many regions world, cardiovascular diseases represent a substantial public health concern, emphasizing the critical importance of preventive measures [25]. It is caused by hypercholesterolemia, a condition in which high levels of cholesterol in blood [26] This is accompanied by other illnesses like obesity and diabetes. The impact of cancer on global mortality rates is substantially higher and stands second after heart attack [27]. Breast, colon, gall bladder, liver and lung cancers are among the most common forms of cancer diagnosed worldwide, posing significant health challenges. Inflammation is a key factor in carcinogenesis and other diseases including obesity, cardiovascular diseases, and cancers[28, 29]. It can modulate the prevention of these deadly diseases. Diabetes is a condition characterized by insufficient insulin production leading to elevated blood glucose levels and potential health complications such as heart diseases, kidney diseases etc., Numerous research revealed consumption of fruits and vegetables could hamper these deadly disease[30]. Bioactive compounds abundant in microgreens have the capacity to modulate various inflammation-related pathways. Hence, microgreens helps in preventing obesity, cardiovascular diseases and diabetes by regulating inflammatory pathway [6]. Several research studies has been conducted on microgreens proving its potential to fight against the chronic disorders. Some of the few clinical studies are presented in Table 2.

Table 2: In vitro studies on microgreens against various diseases

Diseases	Microgreens	Findings	Reference

Cardiovascular diseases	Red cabbage	Lowering cholesterol levels in rats with diet-induced obesity,	[24]
Cancer	Radish, broccoli, kale, and mustard	Colon cancer cells treated with bioaccessible fractions microgreen reduced cell death	[31]
Diabetes	Fenugreek	Inhibited α-amylase by 70 % in cell lines	[32]
	Broccoli	Reduce blood sugar levels in mice	[33]
	Barley	The bio active compounds improved glucose metabolism	[34]
Inflammation	Licorice	Root extracts blocking the pro-inflammatory pathway and cytotoxic impacts	[35]
	Broccoli	Microgreen powder showed reduction in inflammatory markers.	[33]
Obesity	Broccoli	Mice with a high-fat diet demonstrated decreased adipose tissue and body weight	[36]
Iron Deficiency	Fenugreek	an increased iron intake observed in Caco-2 cells	[37]

		, that enhanced the bio accessibility of iron	

4. Production of Microgreens

Microgreens are typically grown in controlled environmental conditions/greenhouses, effectively reducing resource demands and supporting sustainability efforts. A study highlights the resource utilisation of broccoli microgreens, which require substantially less time (93-95%) and water (158-236 times lower) than mature broccoli, while maintaining similar nutrient levels[38]. The preharvest processes influence postharvest nutritional composition of microgreens, and affects quality of these produce.

4.1. Growing Media

Microgreens are raised in soil, cocopeat, peat moss, vermiculite, and jute fabric. The substrate used for microgreens have direct impact on nutritional quality. In neutral and loose soil conditions, like black soil, the fresh weight of red amaranth microgreens increased by 2-3 times. Moreover, the nutritional quality of the microgreens was further enhanced with the addition of compost [39]. But soil posses potential food-safety hazards including microbial contamination [40]. Cocopeat is recognized as a sustainable substitute for soil. however, its high salt concentration and increased fungal and bacterial counts can pose challenges to microgreens production [41]. Moreover, peat, another medium commonly employed, is unsustainable, and jute fibers have relatively lower water holding capacities [42].

Hydroponics and aeroponics are innovative techniques for crop cultivation that eliminate the need for soil by utilizing nutrient solutions as the growth medium. Hydroponics serves as a means of nutrient enrichment for microgreens. Brassicassea microgreens cultivated in a hydroponic system, where they receive daily treatment with suitable nutrients in the growing medium, exhibit a high-quality mineral profile along with a diverse range of macro and micronutrients [43]. Hydroponic solution enriched with selenium content led to a notable increase in both the yield and the concentrations of carotenoids and phenolic compounds in microgreens [44] However, microgreens grown using hydroponic methods have faced microbial safety challenges. Particularly, radish microgreens cultivated in hydroponic systems have exhibited increased concentration of E. coli in comparison to those grown on peat systems [45]. The presence of norovirus has been identified in the consumable parts of microgreens when this virus is introduced into circulating water, as it can be readily absorbed through the roots and cross-contaminated within the circulating water system [46].

An innovative method for cultivating microgreens involves the utilization of hydrogel as the growing medium. Hydrogel, known for its three-dimensional polymeric structure, swells considerably upon water absorption and can sustain hydration for extended durations. Hydrogels have diverse applications in agriculture, including soil conditioning, seed coating, and facilitating the regulated release of water and fertilizers. Hydrogels formulated using sodium alginate for soil conditioning have been found to enhance the growth of lettuce, particularly in drought conditions, as observed within a seven-day period [47]. Red cabbage microgreens, grown in agarose hydrogels supplemented with fillers, achieved 12-day growth cycle without the need for watering, resulting in a notable 54% increase in yield. Additionally, these microgreens have exhibited satisfactory growth under microgravity conditions, signaling the potential for space farming [48].

4.2. Lighting Systems

Indoor farming depends on artificial lighting solutions for year-round plant cultivation. Currently, light emitting diodes (LEDs) are dominant in the indoor farming practices [50]. LED lighting's capacity to modify spectral composition in accordance with plant photoreceptors enables growers to achieve optimal production rates, improved plant growth, and enhance the nutritional profile of the cultivated crops [49]. LED light systems provide a host of advantages in operation and are considered a greener alternative to other grow lights [49,50].

4.2.1 Effect of Light Quality

Light quality significantly influences various factors of plant growth, including morphology, color, flavor, and nutritional content [51,52]. When considering light sources for plant growth, it is crucial to recognize that red, blue, and its combination exhibits a notable advantage over white light and other wavelengths, playing a pivotal role in promoting photosynthesis and controlling various metabolic processes in plants [52]. The investigation into various supplemental LED wavelengths, alongside the fundamental blue, red, deep red, and far red components (455 nm, 638 nm, 669 nm, and 731 nm, respectively), revealed diverse effects on the antioxidant compounds present in germinated seeds. Of notable significance, the introduction of green light (510 nm) demonstrated a remarkable improvement in the antioxidant characteristics of both lentil and wheat sprouts [53]. Supplemental light wavelengths prompted a considerable rise in the metabolic synthesis of diverse bioactive compounds across various plants, indicating their potential role in mitigating mild photooxidative stress. Among the majority of species, this increase was particularly evident in total antioxidant activity. However, the effect of the supplemental wavelengths on amaranth, broccoli, and pea did not demonstrate significant alterations in their antioxidant content. Remarkably, beet microgreens exhibited a decline in antioxidant levels upon exposure to the supplemental light [54]. The study conducted by [54] yielded significant insights into the impact of supplemental light on microgreens. It was observed that the total phenolic content saw a considerable increase across various microgreens. Furthermore, the total ascorbic acid content showed a positive response in broccoli, amaranth, mustard, kale and pea whereas borage and basil microgreens showed a decline in this bioactive compound. Similarly, total anthocyanin levels displayed an increase in amaranth, broccoli, pea, kale and tatsoi while borage, parsley, beet, mustard and microgreens showed a decline in anthocyanin content. Exposure to red-blue and far red spectrum has proven to enhance pigment (chlorophyll & carotenoids) levels in microgreens [55].

Green light (520 nm) exposure resulted in an elevated carotenoid content specifically in mustard microgreens. In contrast, other brassicasea microgreens exhibited higher carotenoid levels when exposed to blue/red/far red lights. When compared to a dark control, the usage of white, red, and blue LED lights showed improvements in the soluble solids and vitamin C contents of buckwheat microgreens [56]. Research carried out by [57] brought to light the positive impact of UV-A irradiation as a supplement to basal LED illumination on the antioxidant characteristics of pak choi, beet and basil microgreens. The addition of UV-A irradiation showcased overall improvements in the antioxidant capabilities of these microgreens. Furthermore, the study identified specific wavelengths of UV-A that particularly benefitted individual antioxidant components.

4.2.2. Effect of Light Quantity

The relationship between light quality and plant physiology is intricately linked to the level of irradiance, making it evident that the same light quality, when delivered at various intensities, can lead to considerable fluctuations in plant biochemistry and nutritional attributes. Study conducted on irradiance levels on the nutritional characteristics of Brassica microgreens. By implementing a lighting system comprising 455, 638, 665, and 731nm LEDs at varying intensities (20, 40, 60, 80, and 100%), with photosynthetic photon flux density (PPFD) values (110, 220, 340, 440, and 546 µmol m^{-2} s^{-1}). The optimal microgreen growth was observed within the range of 330–440 µmol m^{-2} s^{-1}, resulting significantly reduced nitrate concentrations, increased phenolic content, total anthocyanins and antioxidant activity. Interestingly, at lower PPFD levels, the plants displayed high concentration of α-tocopherol across all species. Moreover, tatsoi and pak choi microgreens exhibited enhanced ascorbic acid levels under these reduced irradiance conditions [58].

The extensive research delving into of red-blue LED lighting by scientists revealed intriguing findings concerning Brassicaceae microgreens. The use of 300 μmolm^{-2}s^{-1} intensity & an application time of 16 hours, the study showed that blue spectra helps in enhancing quality of cabbage microgreens. In contrast, brassicaceae microgreens responded most favorably to a lower percentage of blue light, specifically at 5% [59]. Additionally, examining the effect of increasing light intensity ranging 100 to 600 μmolm^{-2}s^{-1}, maintaining a consistent bluered light, yielded intriguing results. All four Brassicaceae species exhibited an enhancement in fresh and dry mass with higher light intensity, while hypocotyl length & hue angle demonstrated a linear decrease in response to intensification of light [60].

In response to high-light conditions, plants showed a robust increase in photosynthetic capacity, facilitated through upregulation of electron transport, ATP synthase complexes and photosystems, and key enzymes involved in the Calvin-Benson cycle. This augmentation of the photosynthetic 'machinery' endows plants with enhanced protection against photo damage, reducing their vulnerability to potential harm caused by intense light exposure. Conversely, low-light conditions trigger specific leaf adaptations, including an enhanced light-harvesting complexes and thylakoid membrane layering, leading to the formation of grana-like structures. These adaptive changes are strategically employed by plants to optimize light utilization and harvesting, allowing for efficient photosynthesis even in environments with limited light availability [61].

The investigation revolved around optimizing the bioactive compounds in wild rocket microgreens, achieved with the use of higher light intensity delivering 272 μmolm^{-2}s^{-1}. The light intensity modulated the biosynthetic pathways responsible for producing resveratrol, catechin, and epi-catechin, key bioactive compounds renowned for their valuable health benefits [62]. To attain maximum biomass in lettuce the light intensity was optimized from 400–600 μmol m^{-2} s^{-1}, by white, red, and blue LEDs. Remarkably, the same cumulative photosynthetically active radiation (CPAR) can be attained through two distinct lighting strategies: employing high-intensity illumination for shorter photoperiods or using low-intensity lighting for longer photoperiods [63]. While numerous studies have extensively explored the impact of light spectrum and intensity regarding plant growth and nutrition, the scientific literature concerning the effects of photoperiod on these vital parameters is relatively scarce. Photoperiod influences the production of essential oils plants [64], including lemongrass [65] and mint [66]. In addition studies have indicated its influence on nutritional profile of baby spinach [67]. Variation in photoperiod can affect the amount of phytochemicals in microgreens that influence the light spectrum and intensity. Broccoli microgreens, subjected to combined red/blue LED light (627/470 nm) at 350 mmol m^{-2}s^{-1}/ low-intensity blue light (470 nm) of 41 mmol m^{-2}s^{-1}, under a continuous 24-hour photoperiod for 5 days, experienced increases in secondary metabolites as well as macro and micronutrients [68].

5. Post- Harvest Quality and Shelf Life of Microgreens

Microgreens are highly perishable products that losses its quality within 1 – 2 days after harvesting in room temperature [69]. It exhibits short shelf life of 10- 14 days after storage in low temperatures [51]. During the germination process, microgreens undergo respiration and metabolize stored carbohydrates, which eventually depletes the carbohydrate source and leads to senescence [70]. They possess delicate and immature tissue structures. Early harvesting and improper handling of microgreens before reaching their mature stage can accelerate senescence, resulting in various physiological, biochemical, and molecular activities that ultimately lead to leaf senescence. The quality deterioration due to induced stress during harvesting and handling is more than the natural senescence. This rapid deterioration limits the industrial production of microgreens.

Due to their high moisture content and nutrient density, microgreens create a favorable habitat for microbial proliferation. Ensuring microbial safety involves considering factors such as the production environment, including pre and post-harvest practices, as well as growing conditions, handling practices, and proper storage. Microorganisms can infiltrate microgreens during the production stage via contaminated seeds, the presence of high humidity in growing conditions, the use of water that is contaminated, and higher seed density [71]. The fungal species, like Pythium dissotocum L. and Pythium aphanidermatum L. are responsible for Pythium root rot as a result of high seed density like in Brassicasea species [72]. The harvesting and handling stages could also promote the growth of microorganisms. Since microgreens are cut in close vicinity to the growing medium, they are highly susceptible to contamination with microorganisms from these medium. The cut section during harvesting is also susceptible to microbial invasions.

There are several methods to delay the senescence in agricultural produce. The most common techniques to enhance the shelf life include lowering the temperature, modifying the storage atmosphere, coating techniques, etc.[73]. Some of the recent innovations are listed here.

5.1 Storage Temperature

Storage temperature constitutes a significant element to prolong the shelf life, to facilitate transportation, prevent spoilage, preserve nutrient value, and ensure freshness over an extended period. Low temperature preserves the microgreens by reducing their physiological activities, such as respiration rate, and hinder the proliferation of microorganisms that causes spoilage [74]. The fresh-cut produce are typically stored at 0°C, and for transportation 5 to 10 °C are commonly utilized [73].

Microgreens stored under low temperature along with pre and post-harvest treatments maintained visual quality and nutritional quality in various studies. Arugula microgreens can be kept at a temperature of 4°C, maintaining their freshness for approximately 14 days. The red cabbage microgreens increased the shelf life at 4 °C by 14 days and at 10 °C by 7 days. [20]. Radish microgreens can be keeped at 4℃, increased the shelf life upto 21 days [20]. When radish microgreens stored at a temperature of 1°C, they exhibit the highest visual quality. Additionally, the gas composition at 1°C is influenced by the packaging film's oxygen transmission rate (OTR) [75]. Cabbage microgreens along with wash treatments, ethanol spray and packaging within polypropylene film yielded the highest quality [76]. When buckwheat microgreens stored at 5°C, in elevated levels of oxygen and low carbon dioxide levels exhibits their maximum shelf life [77].The use of PET clamshell box resulted in better packaging for radish and roselle microgreens, leading to higher postharvest quality [78].

5.2. Relative Humidity

Relative humidity is a critical aspect that significantly influences the quality of fresh-cut products. While dehydration primarily impacts produce quality, excessive humidity poses problems for food safety. The condensation of water on produce surface, commonly known as sweating, over extended periods, fosters microbial proliferation and decomposition to a greater extent compared to high relative humidity of surrounding air. [79]. Further discussion on humidity is provided in the section below, specifically focusing on washing treatments.

5.3 Harvesting at Optimal Maturity

Research highlights the potential impact of harvesting stage on quality of microgreens. According to industry standards, various crops are harvested at specific stages to attain optimal growth. For instance, radish microgreens are typically harvested after seven days, while red cabbage and arugula microgreens are harvested at 9 and 11 days, respectively. Radish microgreens displayed the lowest respiration rate after the initial week of growth, coinciding with the highest quality. Subsequently, when stored at 4 °C, radish microgreens demonstrated a shelf life of 21 days, whereas arugula & red cabbage microgreens exhibited a slightly shorter shelf life of 14 days in the same temperature [80].

5.4 Sanitation and Handling Skill

Effective sanitation practices for equipment involved in the handling and transportation of produce play a pivotal role in safeguarding against cross-contamination and the potential spread of infections from both spoilage and pathogenic microorganisms.

Research conducted by [81], contributed to the understanding of contamination in lettuce production, with their research demonstrating that a single contaminated coring knife consecutively transmitted pathogens to as many as 19 lettuce heads. Similarly, the experiment by [82] emphasizes the pivotal role of worker training and expertise in safeguarding harvested crops. Adequate knowledge and proficiency are essential for executing precise handling practices of crops to attain standard quality [79], while simultaneously minimizing the risks associated with microbial contamination. While specific research on transmission of microorganisms during microgreen production and harvest remains scarce, the application of basic precautions can significantly limit the transmission of pathogens. The sanitation of containers or flats before their reuse in microgreen cultivation is of almost importance. Likewise, sanitizing cutting implements between flats is essential, and stringent measures should be followed to prevent any potential contact with the growth medium.

5.5 Minimizing Injury

Preserving the quality of produce by minimizing injury assumes considerable importance, as injured fruits and vegetables are susceptible to rapid spoilage that provide favorable conditions for pathogen retention. The seminal study conducted by[83] yielded compelling evidence, indicating a significant correlation between soft rot-affected produce and a high prevalence of Salmonella, thereby emphasizing the need for stringent measures to ensure produce safety.

The pioneering work of [84], utilizing confocal laser scanning microscopy, provided crucial insights into E. coli O157:H7 behavior, showcasing its preference for attaching to cut edges in lettuce tissue. Subsequently, [85] revealed E. coli populations in injured lettuce leaves, highlighting the need for stringent measures to prevent physical injury in the delicate nature of microgreens during harvesting, handling, distribution, and marketing.

5.6 Modified Atmosphere Packaging Storage

The harvesting process of microgreens, involving cutting above the root, renders them highly susceptible to rapid deterioration, contingent on the specific plant species [80]. While Modified Atmosphere Packaging (MAP) has demonstrated efficacy in enhancing the shelf life of different crops. The MAP for microgreens remains an area with insufficient research. The undeniable advantage of employing packaging films lies in their capacity to mitigate water loss & shield delicate plants from external contaminants. However, it is noteworthy that certain research reported insignificant differences among films with varying oxygen transmission rates concerning their impact on microgreen quality preservation, even throughout late stages of shelf life, lasting 21 to 28 days[77].

The implementation of Modified Atmosphere Packaging (MAP) necessitates a highly nuanced approach, individualized for each commodity, as the utilization of inadequate modified atmospheres can trigger adverse effects, such as physiological disorders, impaired wound healing, expedited senescence, and increased vulnerability to pathogenic infestations and decay. Careful assessment and optimization of MAP parameters are paramount in safeguarding the quality and marketability of various commodities[79].

The management of CO_2 and O_2 levels within Modified Atmosphere Packaging (MAP) is critical, as elevated CO_2 concentrations can trigger tissue injury, and decreased Oxygen levels can develop anaerobic environments, leading to the generation of undesirable odors and flavors [86]. Striking the right balance in MAP is crucial for maintaining optimal product quality and preserving sensory attributes. The strategic use of low temperatures in MAP has a remarkable impact on microgreens, considerably lowering their respiration rates and maintaining optimal oxygen levels within the package to avert the risk of anaerobic damage[69]. The careful control of temperatures is a vital consideration in enhancing the storage and overall quality of microgreens. Given the impact of temperature on film permeability, the effectiveness of Modified Atmosphere Packaging may vary depending on temperature conditions, with the suitable MAP at particular temperature not necessarily being ideal for other [87]. Therefore, diligent monitoring and control of temperature are indispensable in preserving the desired atmosphere within the packaging. To ensure the effectiveness of MAP, it is crucial to maintain the integrity of the cold chain, typically requiring storage at temperatures below 8 °C.

Within the realm of packaging advancements, active and intelligent packaging technologies have emerged as transformative tools, offering multifaceted benefits encompassing prolonged shelf life, heightened safety measures, real-time freshness monitoring, and comprehensive information display on quality and safety [88]. Among the active packaging solutions, antimicrobial polymers and films stand out for their capacity to effectively impede spoilage and pathogenic microorganisms, enhancing product stability and safety [89]. On the other hand, the intelligent packaging has indicators that deftly react to toxins, enabling timely detection of package leaks, assessing quality deterioration, and precisely monitoring temperature fluctuations beyond predetermined thresholds and durations [90]. Despite the numerous advancements in active packaging technologies, research pertaining to their utilization for microgreen storage has yet to be documented in the literature.

5.7 Post-harvest Light Treatment

Light treatments have been recognized as potential contributors to the improvement of both quality and safety in harvested produce. However, the limited studies examining the impact of post-harvest light treatment on produce that have yielded conflicting outcomes. For instance,[91] observed that Modified Atmosphere Packaging during 24 h period of light and dark treatments led to deterioration of spinach leaves. Specifically, under light treatments, the process of photosynthesis resulted in higher O_2 and lowered CO_2 concentrations that inadvertently stimulated oxidative damage, discoloration, and facilitated the proliferation of microorganisms. Packages held in dark conditions exhibited a distinct response, characterized by respiration-induced fluctuations in O_2 and CO_2 levels, leading to the formation of alkaline compounds and consequent pH elevation. The effects of light exposure on lettuce quality were evident, with uninterrupted light caused elevated O_2 levels and undesirable browning of lettuce, while storage in darkness caused CO_2 injury and fostered anaerobic environment in packaging materials. The study revealed that a 12-hour photoperiod treatment provided some mitigation of discoloration compared to constant light exposure, and reduced tissue injury in comparison to continuous darkness [92]. The continuous light exposure at 4 °C increased bioactive compounds in spinach leaves, however this improvement was accompanied by a heightened susceptibility to wilting compared to leaves stored in continuous darkness [93]. In fresh-cut broccoli, [94] demonstrated that subjecting it to continuous light at 24 µmol $m^{-2}s^{-1}$ during 10 day storage at 7 °C led to notable preservation of bioactive compounds compared to darkness. However, the light treatment also led to an accelerated fresh weight loss, presenting a trade-off between nutrient retention and shelf life. [95] indicated the capacity of light treatments in significantly extending the shelf life of broccoli, with green light emerging as particularly beneficial in preserving essential bioactive compounds, such as phenols and glucosinolates, compared to fluorescent light. Conversely, the research by [75] on radish microgreens revealed that light exposure during storage expedited the deterioration process, whereas dark storage maintained overall quality. The findings also suggested an increase in ascorbic acid levels under light exposure, with no significant impact on α-tocopherol or total phenolic concentrations.

5.8 1-Methylcyclopropene

Despite the well-established effectiveness of 1-methylcyclopropene (1-MCP) in enhancing postharvest longevity of various fruits, vegetables, and edible flowers, its potential application and impact on microgreens remain unexplored in the scientific literature. The influence of ethylene on horticultural crops extends beyond maturation processes, with documented effects on discoloration, decay, and the activation of defense systems to cope with environmental stressors. MCP helps in inhibiting ethylene, leading to prolonged postharvest preservation of various fruits and vegetables. [96]. Research demonstrated by [97] showed the potential of 1-MCP in delaying senescence, an attribute encompassing leaf yellowing, abscission, and spoilage, in wide variety of vegetables. In the context of leafy vegetables, [98] explored the impact of this treatment on shelf life, with interesting findings showing varied responses, depending on the existence or lack of ethylene. A study by [98] revealed intriguing results regarding 1-MCP treatment, indicating its capability to prolong the quality of tatsoi and mizuna in the absence of ethylene, while significantly protecting mustard and chrysanthemum when ethylene was present. 1MCP's versatility as an ethylene perception inhibitor was highlighted in the studies by [97,98] , illustrating its potential application in maintaining post-harvest quality and delaying senescence in a diverse range of vegetable species.

5.9 Washing Treatments

Washing treatments holds significance in extending shelf life by effectively rinsing away exudates that nourish the microbes, thus decreasing the overall microbial load. Additionally, washing provides essential moisture to delicate greens that are prone to dehydration, thereby contributing to improved shelf life. Washing ruby radish microgreens with a 100 ppm chlorine solution and employing gentle centrifugal drying to maintain product quality. However washing can sometimes result in higher moisture content within the packaging, that may stimulate microbial growth, decay, and potential damage to delicate greens. The delicate nature of microgreens necessitates precision in the washing and drying processes to preserve their inherent nutritional value and prevent microbial spoilage. Exploring novel technologies that minimize damage and quality deterioration is vital to fulfilling consumer expectations for extended shelf life. The study by [69] highlighted the critical role of washing treatments in preserving the quality of "Tah Tasai" Chinese cabbage microgreens during cold storage. While traditional washing methods resulted in rapid quality deterioration, innovative washing approaches involving citric acid and ascorbic acid demonstrated extended shelf life up to day 7.

In studies conducted by [75] on radish microgreens and [77] on buckwheat microgreens, it was observed that washing treatments led to accelerated deterioration compared to unwashed microgreens. The deterioration was attributed, to damage caused at the time of the washing and draining process, and also from excessive moisture retained in packages of these microgreens. Interestingly, Microbial levels rinsed with chlorine showed an initial drop, followed by a subsequent resurgence, exceeding the microbial counts of unwashed microgreens by the end storage period of 21 days. The research conducted by [99] offered valuable insights into postharvest wash treatments in maintaining the quality of broccoli microgreens. The 50 mM calcium lactate dip showed some advantages over the chlorine dip; however, both postharvest wash treatments resulted in a notable decline in quality when compared to the efficacy of preharvest calcium chloride treatment.

Studies suggest that wash treatment prior to storage could reduce the microbial load associated with microgreens. Several wash treatments performed on Chinese cabbage microgreens including normal water, chlorine, ascorbic acid, citric acid ethanol spray. The study demonstrated combined effect of citric acid and ethanol showed lowest microbial count [69]. Rinsing microgreens with double distilled water for a duration of 2 min has exhibited a partial decrease in microbial population [102]. Chlorine wash treatment of radish microgreens reduced yeast and mold and aerobic mesophilic bacteria count by 0.5log cfu g^{-1} initially but growth reoccurred after 7 day of storage [75].

5.10 Edible Coating

Edible films and coating are materials used for enrobing variety of food items with the goal of extending their shelf life [100]. It acts as a primary package and protects the products from spoilage, extends the quality of products. They are composed of polysaccharides, proteins and lipids and other active ingredients hence improving safety, nutritional and sensory characteristics [101].

Microgreens, categorized under fresh-cut produce, have also been subjected to edible coating techniques. Post-harvest quality of radish and hibiscus microgreens coated with aloe vera gel has been studied, and it has been found that the microgreens retained overall acceptability and preserved ascorbic acid content during storage. Radish maintained marketability until the 12^{th} day, but hibiscus showed wilting symptoms on the same storage day. The coating also reduced the microbial load. The aloe vera gel spray coating was found to be better than the aloe vera dip coating. Dip coating can cause contamination and mechanical injury. The microbial load for dip coating was higher when compared to spray coating [78].

Similar study was conducted on broccoli microgreens that utilized calcium chloride and calcium lactate treatments. Preharvest calcium application extended the quality till 14 days, when compared to control samples with 7-day shelf life. Conversely postharvest dip treatments reduced the quality of microgreens compared to pre harvest treatment as a result of tissue damage occurred during spinning and drying stages [99].

5.11 Value Addition in Microgreens

Microgreens, which are nutrient-rich, can be transformed to value-added products through processing. Researchers have explored the application of microgreen extracts in various studies. A research on Broccoli microgreen juice revealed that it serve as a functional food for obesity [36].

Additionally the microgreen juice extract is also incorporated with many other juice products [103]. It has also been incorporated into chutney powders. For example, different formulations of fenugreek microgreen powders were added to common chutney powders, resulting in favorable sensory scores [104]. Chutney powders made from a variety of microgreens, including fenugreek, green gram, horse gram, and mustard, were developed, and it was found that green gram microgreens received high sensory acceptability [105]. Processing microgreens also addresses the issue of shelf life. Microgreens are also incorporated into processed food products. For example, bread enriched with lupin preserves genistein, a flavonoid compound that aids in bone health and helps prevent cancer [106]. Muffins enriched with mung bean and wheat microgreens exhibited elevated protein levels , dietary fiber and other bioactive compounds. However, the sensory evaluation of the mung bean muffins yielded unsatisfactory results. On the contrary, incorporating 2% wheatgrass showed great promise in enhancing the nutritional value of gluten-free, eggless rice muffins [107].

6. Conclusion and Future Work

Microgreens have emerged as a superfood to alleviate deficiencies and a way to sustainable food production. With their distinctive flavors enhancing culinary dishes, salads, and providing essential nutrients to the diet, microgreens have gained increasing demand due to their numerous health benefits. Remarkably, they have even proven to be a life-supporting system during space missions, proving their potential in unconventional environments. Despite their numerous advantages, the limited shelf life of microgreens currently poses a challenge to their widespread production. To fully unlock their commercialization potential and address future issues like food security, several strategies must be developed. These strategies will be crucial for extending shelf life, optimizing cultivation techniques, and ensuring efficient distribution networks, ultimately paving the way for a more sustainable and accessible microgreen industry.

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