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Hydroponic Production Systems: Impact on Nutritional Status and Bioactive Compounds of Fresh Vegetables

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Abstract

Hydroponic systems for vegetable production are nowadays essential to maximize productions and increase yields. Although the technical issues concerning the production are well explored and discussed, less information is available about the impact of hydroponic methods in the nutritional status of fresh vegetables and in particular in their levels of bioactive compounds. Therefore, the aim of the current chapter is to provide accurate and updated information about their effects on compositional and bioactive properties of vegetables, comparing with conventional production mode. This chapter will be divided as the following sections: (1) introduction (introduction to the theme), (2) hydroponics and quality of vegetable produces, and (3) conclusion. With this chapter, we hope to present an updated and credible discussion, compare hydroponic versus conventional vegetables production mode, and present new consumers and producer trends.

Keywords: hydroponics, conventional production, nutrients, bioactivities

1. Introduction

Hydroponics can be briefly defined as cultivation of plants without soil [13]. In short, hydroponics, a Greek word meaning “hydro” (water) and “ponos” (labor) is the method of growing plants in different types of substrates (chemically inert), sand, gravel, or liquid (water), in which nutrients are added, but no soil is used [13, 14].

Actually, Europe is considered the biggest market for hydroponics in which France, the Netherlands, and Spain are the three top producers, followed by the United States of America and Asia-Pacific region. These systems are becoming increasingly widespread over the world, and according to the most recent report [15], it is expected to reach a world growth of 18.8% from 2017 to 2023, corresponding to a global hydroponic market USD 490.50 Million by 2023.

According to growers, hydroponic systems help them in expanding their ability for a continuous production in a short growing period, require less space, and plants can be produced anywhere, i.e., in a small spaces with a controlled growth environment [16]. Growers often reply that hydroponics always allows them to have higher productivities and yields without any constraints of climate and weather conditions [17]. In addition, growers often claimed that quality of hydroponic produces is superior because it uses a highly controlled environment and enables a more homogeneous production without any loss of water and nutrients. Moreover, hydroponics is not dependent on seasonality, and therefore, their productivities are higher and homogenous throughout the year [18]. Growers also often report that hydroponic productions are easier, and since they do not require cultural operations such as plowing, weeding, soil fertilization, and crop rotation, they are light and clean [19]. However, the scientific evidences are often contradictory and different disadvantages are reported to justify their rejection: high initial costs, high technical and plant physiology knowledge, periodic work routines, and efficient electrical systems [4, 19, 20]. It is also necessary and effective to control nutritional solutions and take daily measurements of liquid nutrients to avoid excess salinization and control microbial diseases and pests to avoid any loss of production [4]. Nonetheless, growers often argue that this technique allows the possibility to grow healthier food and helps in the reduction of wastes. An example of this waste reduction can be seen in lettuce, the most hydroponically cultivated crop in the world, in which about 99% of their hydroponic leaves are valid and they can be sold to a value approximately of 40% more expensive than a lettuce grown traditionally [4]. Moreover, with hydroponics, there is a better opportunity to place the fresh produces in the market since their average nutritional quality and consumer's acceptance are higher [21]. In addition, growers reported that with hydroponics, some of the negative impacts of conventional agriculture are avoided including high and inefficient use of water, large land requirements, high concentrations of nutrients and pesticides, and soil degradation accompanied by erosion [22, 23]; issues that are much more in the nowadays concerns of consumers.

Worldwide consumers are increasingly interested in having more environment-friendly fresh vegetables due to the strong and well-established inverse relationship between vegetable consumption and the risk of many types of chronic and degenerative diseases like cancer, cardiovascular, and neurological disorders [1]. Because of this growing consumer interest, the content of health-promoting compounds is becoming a vital consideration for fruit and vegetable growers. In fact, fresh vegetables and fruits are rich sources of bioactive compounds with significant health benefits, and these beneficial compounds can be influenced by several key factors including genotype selection and environmental conditions (light, temperature, humidity, atmospheric CO₂). Contrary to the conventional agricultural system, hydroponic relies on the manipulation of nutrients, which according to different authors allows having produces with high accumulation of some beneficial nutrients [3, 5]. However, questions about their safety are often raised.

There are considerable research studies regarding conventional and hydroponic production separately, but few have compared the impact of both on the nutritional quality of fresh vegetables. In this context, with this chapter, we discuss with updated information on the differences between of hydroponics and conventional production and the impact of hydroponics in the nutritional composition and bioactive compound levels. We debate their impact, limitations, and success.

2. Hydroponics and quality of vegetable produces

2.1. Hydroponic systems: Definition of hydroponics and brief description of main hydroponic systems

Hydroponic production is the method of growing plants under soilless (i.e., soil less) conditions with nutrients, water, and an inert medium (gravel, sand, perlite among others) [13, 14].

From the perspective of plant science, there are no differences between soilless and soil-grown plants, because in both systems, the nutrients must be dissolved in water before plants can absorb them [24]. The differences reside in the way of nutrients that are available to the plants. In hydroponics, the nutrients are dissolved in water and the solution goes into the plant roots, which uptake the water with minerals toward different parts of plant. In the soil-based production, the elements stick to the soil particles, pass into the soil solution, where they are absorbed by the plant roots [24, 25].

There are different types of hydroponics, depending on how they are characterized. One criterion is to classify as closed or open hydroponic systems [25, 26]. The hydroponic systems that do not use growing media are usually referred as closed systems, while hydroponic systems with growing media in a container may be closed or open depending on whether the nutrient solution is recirculated (closed) or is introduced on every irrigation cycle (open). In the closed systems, the nutrient concentrations are constantly recycled, monitored, and adjusted, while in open systems, the nutrient solution is discarded (but stored) after each nutrition cycle.

Another approach to classify hydroponic systems is to classify them based on the movement of the nutrient solution: active or passive [26, 27]. Active means that nutrient solution will be moved, usually by a pump, and passive relies on a wick or the anchor of the growing media. Others characterize the hydroponics with recovery or nonrecovery criteria [26, 27]. Recovery is when the nutrient solution will be reintroduced into the system, while nonrecovery means that nutrient solution is applied to the growing media and vanish after that.

Although there is a large diversity of criteria, there are three fundamental things for plants: (1) water/moisture, (2) nutrients, and (3) oxygen. All these different types of hydroponics must deliver those three important fundamental things to achieve success in plant production. Despite this diversity, the criteria most commonly used by growers, farmers, private companies, and researchers categorize hydroponic systems into six different types [26–28]: Nutrient film technique (NFT), wick system, ebb and flow (flood and drain), water culture, drip system, and aeroponic system. **Table 1** summarizes the main characteristics of each system.

2.2. Bioactive compounds

2.2.1. Definition of “bioactive compounds”

According to Biesalski et al. [2], it is widely accepted that bioactive compounds can be defined as essential and nonessential compounds that occur in nature as part of the food chain and with positive effect on human health. Bioactive compounds consist of chemicals found in small volumes in plants

(leaves, roots, shoots, bark) and foods such as fruits, vegetables, nuts, oils, cereals, and grains [29]. Bioactive compounds result from secondary metabolites of plants and are not essential for their daily functioning but play a significant role in the defense, attraction, signaling, and competition and thus are often named as secondary plant metabolites [30, 31].

2.2.2. Types and main groups of bioactive compounds in vegetables

Bioactive compounds may be classified according to different criteria. The most common classification used by literature is based on their pharmacological and toxicological effect. However, this is more relevant to the clinicians, pharmacist, or toxicologists and not for plant biologists, agronomists, or other researchers involved in plant-related studies. For these last groups, it is normal to classify them according to biochemical pathways and chemical classes.

Table 2 summarizes the main classes of bioactive compounds often found in plants and foods.

Hydroponic system	Description
Aeroponics	This is the most sophisticated and high-tech method, in which plants are suspended in special trails. Nutrients are sprayed, every few minutes, directly to the roots, which provide a light layer of nutrients. This system requires a regular monitorization of pumps to avoid any failure.
Deepwater culture (DWC)	In a DWC system, a reservoir is used to hold the nutrient solution. The roots of plants are suspended the nutrient solution in order to get a constant supply of water, oxygen, and nutrients. In this system, an air pump is used to oxygenate the water, preventing the roots from drowning.
Drip system	In this system, the nutrient solution is set apart in a reservoir, and the plants are grown separately in a soilless medium. Drip systems dispense nutrients at a very slow rate, through nozzles, and the extra solutions can be collected and recirculated, or even allowed to drain out. With this system, it is possible to simultaneously grow several kinds of plants.
Ebb and flow	Also known as “flood and drain,” is the less-commonly used system in hydroponics. This system utilizes a grow tray and a reservoir that is filled with a nutrient solution. A pump periodically floods the grow tray with nutrient solution, which then slowly drains away. In this system, plants are normally grown in mediums like rockwool or gravel, but if they need a substantial amount of moisture, this is substituted with vermiculite or coconut fiber due to their high capacity of excess moisture retention between floodings.
Nutrient film technique (NFT)	Similar to aeroponics, the nutrient film technique (NFT) is the most popular hydroponic system. In this method, a nutrient solution is pumped constantly through channels in which plants are placed. When the nutrient solutions reach the end of the channel, they are sent back to the beginning of the system. This makes it a recirculating system, but unlike DWC, the plants roots are not completely submerged, which is the main reason for naming this method NFT.
Wick system	<p>This is the easiest and simple method of hydroponics. It is a completely passive system, which means that nutrients are stored in a reservoir and moved into the root system by capillary action. With this system, we can find a diverse variety of growing medium such as perlite, vermiculite, coconut fiber, and other formulations.</p> <p>The wick system is easy and inexpensive to set-up and maintain. The biggest drawback of this system resides in the poor oxygenation of plant roots and the large amount of nutrient solution that is required to reach efficiently to the plant root system.</p>

Table 1. Main types of hydroponic systems and their respective characteristics, according to growers, farmers, private companies, and researchers [18–20].

Chemical class	Health benefits	Example of primary food sources
Vitamins (C, E, and K)	Antioxidative protection of cells and membranes against reactive oxygen species (ROS), protection of lipoproteins, stabilization of cell membrane structures, modulation of immune response, inhibition of tumor growth in humans.	Fruits and vegetables.
Glycosides (cardiac glycosides, cyanogenic glycosides, glucosinolates, and anthraquinone glycosides)	Recent reports provide a large number of evidences about the chemopreventive role of different type of glycosides against cancers (bladder, prostate, esophagus, and stomach) and cancerous deleterious degenerative diseases. The glucosinolates, one of the most relevant group of glycoside compounds, are capable to activate enzymes involved in the detoxification of carcinogens, thus providing protection against oxidative damage.	Cruciferous vegetables, garlic, leek, onion.
Phenolics (natural monophenols and polyphenols including phenolic acids, flavonoids, aurones, chalconoids, flavonolignans, lignans, stilbenes, curcuminoids, and tannins)	The specific action of each phenolic is difficult to assess, because organisms absorb only a small part of it and in addition, they may suffer transformations. Epidemiological studies have claimed that polyphenols are capable of scavenging reactive oxygen species (ROS), inhibiting the peroxidation lipids from cellular membranes, preventing the LDL cholesterol from oxidation, and protecting DNA from mutations and oxidations.	Fruits and vegetables, tea, cocoa, wine, grapes, peanuts.
Carotenoids (carotenoids endowed with provitamin A activity, which are vital components of the human diet)	Although their bioactive mechanisms are still poorly understood, the health importance of carotenoids is normally discussed in terms of antioxidant properties. Carotenoid-rich diets are correlated with a significant reduction in the risk of certain cancers, and heart and degenerative diseases. Epidemiological studies have shown that carotenoids may have anticancer and antimutagenic properties.	Green, orange, red, and yellow vegetables.
Plant sterols (phytosterols)	They regulate the fluidity and permeability of the phospholipid bilayers of plant membranes. Plant sterols have been hypothesized to have anticancer, antiatherosclerosis, anti-inflammation, and antioxidant activities.	Cruciferous vegetables, spinach, rice, soybean, wheat germ, wheat bran, nuts, and vegetable seeds.
Alkaloids (morphine, cocaine, solanine, caffeine)	Morphine, cocaine, solanine, and caffeine are the most relevant alkaloids in plants. Besides the toxicity and their addictive effect, morphine and cocaine have been used in different formulations as anesthetics. The caffeine, the most known alkaloid and in high concentrations, is toxic and protects the plant seedlings from pests and plagues and prevents the germination of any other plants in the area (allopathic effects). In humans, caffeine has also been thought to reduce the risk of diabetes and heart disease, and recently, it has been associated with prevention of Alzheimer and Parkinson's diseases.	Papaveraceae (poppy family), coffee, cocoa, tea, Solanaceae (nightshade family), sweet peppers, chili peppers, jalapeno peppers eggplant, tomatoes, potatoes <i>Atropa belladonna</i> (deadly nightshade), <i>Datura</i> spp. (thorn apples).
Saponins	Among other properties, saponins are referred as having cardioprotective and hepatoprotective effects. Saponins have been observed to reduce blood cholesterol, stimulate the immune system, and inhibit the growth of cancer cells.	Beans, grains, chickpeas, oats, quinoa, asparagus, soy, red wine, and melons.

Table 2. Main classes of bioactive compounds commonly found in plants, classified according to chemical class criteria [1, 2, 24–26].

2.3. Hydroponic and accumulation of bioactive compounds

Soil farmers experience these same types of variations with respect to soil health and fluctuations in environmental conditions. For example, water quality and variations in temperature and humidity can place stress on crops potentially changing their biochemical makeup regardless of the growing method being used. Because of these variations, studies to date comparing the nutritional content of produces grown hydroponically to soil grown have had mixed results, with some studies showing no difference between the two methods, while others showing that soilless systems fared either better or worse than soil-grown controls in the nutrient levels being tested. As you can imagine, experimental design and conditions vary widely between these studies and depend on how they were designed affecting the outcome and the significance of the findings.

Different studies have claimed that vegetables produced from hydroponics have better qualities than those from conventional soil-based cultivation [32, 33]. On the other hand, other studies have claimed that the exact differences between qualities of vegetables grown in soil or hydroponics are difficult to establish [10, 34, 35]. Nonetheless, all authors in general seem to agree that hydroponic systems can be the best alternative when arable soil is scarce or their types are not ideal for the desired crop.

Although there are diverse and contradictory opinions, the general view of researcher seems to be that hydroponic can enhance the content of bioactive compounds. Recent studies have shown that in some high-value fresh vegetables, the hydroponic systems allow having higher nutritional quality due to high accumulation of bioactive compounds. Premuzic et al. [36] found an increment of macro- and micronutrients as well as in antioxidants in hydroponic tomatoes, compared to soil-based production. Selma et al. [37] found that hydroponic system was more effective in controlling microbial contamination as well as higher antioxidant compounds, since this method of production allowed a better maintenance of visual quality, control of browning, and more effective in controlling microbial contamination as compared with lettuces cultivated in soil. Pedneault et al. [38] in *Achillea millefolium* found an accumulation of flavonoids in plants grown in hydroponic systems (0.43% dry weigh) compared to field-grown plants 0.38% dry weight). Also, Sgherri et al. [3] found that hydroponic cultivation of basil (*Ocimum basilicum* cv. Genova) improved the antioxidant activity of both aqueous and lipid extracts, increasing the contents of vitamin C, vitamin E, lipoic acid, total phenols, and rosmarinic acid. **Table 3** presents some examples of studies about the accumulation of bioactive compounds under hydroponic systems.

Based on the results obtained by the different authors, it seems evident that all of them reported as common reasons for the enhancement of bioactive compounds under hydroponics—the tight control over the entire process of cultivation, particularly the amount and composition of nutrients and environmental conditions of temperature, humidity and light, and water salinity. Hydroponic operations, including the water recirculation systems, may provide ideal conditions for enactment of secondary metabolites, particularly when plants are placed under osmotic or salt stress, which boost the natural bioactive compounds of plants. Moreover, the saturation of light and temperatures by leaf receptors, often used in these systems, contributes

Crop	Results	Reference
Basil	The hydroponic cultivation improved the contents of vitamin C, vitamin E, lipoic acid, total phenols, and rosmarinic acid, as well as their antioxidant activities.	[3]
Lettuce	Hydroponics offered 11 ± 1.7 times higher yields compared to conventionally produced, but also required 82 ± 11 times more energy.	[4]
Lettuce	Levels of alpha-tocopherol here were higher in hydroponics compared to conventional soil-based production.	[5]
Lettuce	The content of lutein, beta-carotene, violaxanthin, and neoxanthin were lower in hydroponics compared to the soil-based production, due to less exposure of hydroponics to sunlight and temperatures, which had significant impact on carotenogenesis decreasing their levels.	[6]
Lettuce	Hydroponics-grown lettuce had significantly lower concentration of microorganisms compared to other in-soil-grown lettuce.	[7]
Onion	Total flavonoids were similar between hydroponics and soil-based cultivation.	[8]
Red paprika	The content of carotenoids capsorubin and capsanthin was higher in hydroponics (4.50 and 46.74 mg/100 g dry weight, respectively) compared to convention soil culture (2.81 and 29.57 mg/100 g dry weight, respectively).	[9]
Strawberry	Fruit yield per plant was 10% higher in hydroponic raspberries compared to soil-grown raspberries.	[10]
Sweet potato	Carotenes, ascorbic acid, thiamin, oxalic and tannic acids, and chymotrypsin and trypsin inhibitors were higher under hydroponics.	[11]
Tomato	No significant differences between hydroponic and nonhydroponic tomatoes in the levels of lycopene content (averaging 36.15 and 36.25 $\mu\text{g/g}$, respectively).	[11]
Tomato	Highly controlled conditions of electrical conductivity (EC) and salinity of water, pH, and nutrients provide optimum condition for enhancing the levels of sugars, Brix, pH, and organic acids, which are quality criteria of consumer acceptance toward tomato.	[12]

Table 3. Comparative results between hydroponics and conventional soil-based production.

to maximize photosynthesis and subsequent carbohydrate production that will be used for different biochemical mechanism including bioactive compounds biosynthesis, enhancing their content. For example, Greer and Weston [39] found that in a controlled environment with lower temperatures, the content of anthocyanin in berries increased. Other authors observed an increment of phenolic acids, flavonoids, and anthocyanins when the ratio of day/night temperature and day/night length was modified from low to high [40]. Also, in a recent study [41] with rocket salads (*Eruca sativa*, *Eruca vesicaria*, and *Diplotaxis tenuifolia*), it was found that setting long day lighting (16 h light, 8 h dark) at an intensity of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$, with a daytime temperatures of 20°C and night-time temperatures of 14°C , caused an enhancement in the content of polyphenols and glucosinolates. Likewise, day/night temperatures and day/night length, the nutrient solutions, the type of lights, and the levels of CO_2 can be used to enhance the content of bioactive compounds. Nutrient solutions with high electrical conductivity (EC) were shown to be efficient in the increment of lycopene (from 34 to 85%) in tomato cultivars [42]. In a study

with *Gynura bicolor* DC (a traditional vegetable from China and South East Asia) submitted to 80% red light and 20% blue light, supplemented with CO₂ elevation from 450 (ambient reading) to 1200 $\mu\text{mol mol}^{-1}$, the content of bioactive compounds enhanced significantly [43]. The content of anthocyanins and flavonoids rose from 400 to 700 mg 100 g⁻¹ dry weight and from 250 to 350 mg 100 g⁻¹ dry weight, respectively [43]. Therefore, growing plants in a highly controlled environment might be an efficient alternative to maximize the production of bioactive compounds.

Although there are many advantages of the hydroponics compared to soil-based production, there are several aspects to be taken in account when we decide to choose hydroponics. These types of production systems require a regular irrigation and fertilization, which may otherwise result in possible contamination of surface and groundwater. In addition, they required an adequate management of pH, electrical conductivity (EC), dissolved oxygen, and temperature of nutrient solutions, because the ion concentrations may change with time, resulting in a nutrient imbalance. Therefore, real-time and periodical measurements of nutrient solutions are required, and adjustment of nutrient ratios is often required. In addition, to avoid infestations and diseases, disinfection systems are obligatory. All these aspects must be considered to achieve high quality without compromising the production yield and safety.

3. Conclusions

Hydroponics is extending worldwide and such systems offer many new alternatives and opportunities for growers and consumers to have productions with high quality, including vegetables enhanced with bioactive compounds. This chapter presented a general overview about the role of hydroponics in the enhancement of these important types of nonessential nutrients, and based on the above discussion, it seems that hydroponics can be an essential instrument to have vegetables with high nutritional quality. However, both hydroponics and soil-based production systems require proper control, and they must be implemented correctly with full respect with plant needs, soil, water, environment, growers, and consumer safety.

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Conflict of interest

The author declares no conflict of interest.

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