Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics

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ABSTRACT
This review paper describes a novel approach to plant cultivation under soil-less culture. At present, global climate change is expected to raise the risk of frequent drought. Agriculture is in a phase of major change around the world and dealing with serious problems. In future, it would be difficult task to provide a fresh and clean food supply for the fast-growing population using traditional agriculture. Under such circumstances, the soil-less cultivation is the alternative technology to adapt effectively. The soil-less system associated with the Hydroponic and Aeroponics system. In the aeroponics system, plant roots are hanging in the artificially provided plastic holder and foam material replacement of the soil under controlled conditions. The roots are allowed to dangle freely and openly in the air. However, the nutrient rich-water deliver with atomization nozzles. The nozzles create a fine spray mist of different droplet size at intermittently or continuously. This review concludes that aeroponics system is considered the best plant growing method for food security and sustainable development. The system has shown some promising returns in various countries and recommended as the most efficient, useful, significant, economical and convenient plant growing system then soil and other soil-less methods.

INTRODUCTION
One of the greatest challenges of today is to end hunger and poverty while making agriculture and food systems sustainable. However, providing clean and fresh food for next generation is our main concerns especially for growing global population (Alexandrats and Bruinsma 2012). The world food production is rising faster than population and per capita consumption increase. Studies reported that in 2050, the world population expects to surpass ten billion people, 34% higher than now. Nearly much of population increase will occur in the developing countries (Cohen 2002; UN 2010). According to FAO (2009, 2011) report, the high concentration of people has major socio-economic ramifications, food production, supply and security issues which require closer examination. Also, it will highlight the several problems, challenges and cause to increase the number of hungry and malnourished people. In 2050, additional 60% to 70% global food production will need to feed the more urban and larger population (Foote 2015).

In the future, the additional pressure will be working on how we more efficiently utilize the natural resources to produce food. The natural resources include soil, water, air and how to use them in sustainability. However, around the quarter of arable land has been declared unproductive, unfertile and unsuitable to perform agriculture activates. The reasons behind these issues are inadequate soil management, soil degradation, fast regional climate changes, rapid urbanization, industrialization, fewer recovery chances of natural fertility, continuous cropping, the frequent drought, less water management, water pollution and the decrease in groundwater (Popp et al. 2014). Blesner et al. (2005) reported water is another critical resource. The scarcity of water is the most important and crucial issue to perform agriculture activities and inflicting insecurity on the social problems. The problems include minimum crop production with high population: (i) Highly dependent on climatic conditions and poor growing season due to starving in different parts of the world, (ii) Higher demand for biofuels could further influence on inputs, prices of farm produce, land, water, and endanger a global food security. As mentioned above, resource constraints for agricultural production have become more stringent than in the past while the growth of yields is slowing down. It is a primary reason why people express fears that there are growing risks that world food production may not be enough to feed a growing population and ensure food security for all. However, it could be challenging to provide supplemental food products to feed the entire population using traditional/open field cultivation system.

Although, the open field cultivation associated with enormous risks and uncertainties from biotic and abiotic stresses, such as pest attacks, droughts, floods and high winds. As it required the larger area for cultivation, higher land preparation cost, number of labors and the excess amount of water.

Under such circumstances, researchers search out the new farming technologies and suggested that the proposed solution is to implement the currently accessible technologies under a controlled environment. In recognition of this, the soil-less system is one of them. Butler and Oebker (2006)
reported that soil-less is the method of plant cultivation without the use of soil within substrate culture or water culture. The technique facilitates many socio-economic benefits including the ability to deal with the increasing global food challenges, environmental changes for the mitigating, malnutrition, management and efficient utilization of natural resources. Furthermore, the soil-less technique can provide continues, enough, fresh, clean and hygienic vegetable supply throughout the year without any interval. The system uses minimum input and facilitates to multiple plant harvesting with maximum output. The concept of the soil-less culture seeks to offer an innovative solution to ensure the environmental and economic sustainability of food supplies with high nutritional quality. It is a highly recommended plant growing technique for all countries having less arable land, rapid environmental changes and increasing food challenges with the indigenous population (Pual 2000; Sardare and Admane 2013). Naville (1913) reported that several ancient civilizations practiced the technique. While the first symbol of container-grown plants documented paintings were found on the Walls of ancient temple Deir el Bahari. Although, many hundred years ago in B.C., Aztecs and Egyptians hieroglyphics also used water culture to grow the specific plants and the hanging garden of Babylon is also an excellent example. In 1627, Francis Bacon published the book named Sylva Sylvarum and John Woodward published work in 1699 and discussed the soil-less culture.

Singh et al. (2010) said that presently several soil-less techniques had been practiced to grow the plant under controlled conditions. Although, it primarily associated with the method of Hydroponic and Aeroponics. According to Farran and Mingo-Castel (2006) the term Hydroponic and Aeroponics have been taken from the Greek and Latina terms Hydro and Aero which means water and air whereas Ponic means (labor) respectively. In both systems, the plant grows without soil by providing the artificial supporting structure under controlled conditions. The plant roots survive in the air under mist environment or wholly immersed in nutrient rich-water (Beibel 1960; Reyesa et al. 2012).

Overview and concept of the aeroponics system

Aeroponics is the science of plant cultivation without incorporation of the soil or a substrate culture. Where plant grows in the air with the assistance of an artificial support and no soil or substrate is required to support the plant as shown in Figures 1 and 2 (Osvald et al. 2001). Basically, it is an air water culture cultivation system, the roots of plant are hanged inside a sealed container under darkness and openly exposed in the air to get water nutrient-rich spray through atomizers. The upper portion of the plant leaves and crown extend above the wet zone. The root and canopy of the plant are separated by the artificially provided structure. The system uses the nutrient-enriched spray in the air with the help of pressure nozzles or foggers to sustain hyper growth under controlled conditions (Nir 1982; Engenhart 1984; Zsoldos et al. 1987; Barak et al. 1996; Mbiyu et al. 2012). US Patent Publication No 1999/5937575A defined that Aeroponics system provides many advantages for agricultural research and production as a modern research tool. However, the concept and idea of plant cultivation in the air by providing artificial support and environment is not much old. The researchers acquired the idea to see the most of the growing plants on rocks near the waterfalls. They frequently observed that plants were successfully grown on rocks near the waterfalls. Although, the roots of plants are openly hanged in the air. It was the logical extension for plant growing in air under spray mist condition. Rains (1941) reported that generally in nature these conditions happen on tropical islands like Hawaii. Throughout the literature survey on the historical overview of the aeroponics system. It was found that in the early 1921s, Barker (1922) first developed primitive air plant growing system and used for laboratory work to investigate the plant root structure. He reported that air plant growing technique is the natural and simple practice to grow plants without incorporation of soil. The absence of soil made study much easier: roots of plant hanged in midair while the stems detained in artificial place (Peterson and Krueger 1988). In 1940, the technique was frequently used by many researchers as a modern research tool in plant root studies (Christi and Nichols 2004; Chang et al. 2008). Carter (1942) studied the air-growing culture and cultivated the pineapple plant. He concluded that air-growing culture is useful technique for plant roots studies. The air-growing culture reduced the mechanical injuries and interferences with significant growth compared with soil, sand, or even aerated water culture. The discrete nature of atomization spray interval and duration allows for measuring the nutrient uptake concentrations within the plant over time under different conditions. The atomization spray provides the intermittent mist of nutrients to plant root on different periodic intervals for the specific duration rather than a permanent misting. Klutz (1944) was the first researcher to discover vapor misted citrus plants. He did the work to facilitate his research studies of diseases of citrus and avocado roots. Vyvyan and Travell (1953) successfully grew apple plants under mist environment. Went (1957) at the Earhart Laboratories in Pasadena, California grew tomato and coffee plants in a water-tight container with fine nutrient mist propelled by atomization injector with pressure. He named the method as ‘Aeroponics plant growing system’ (Stoner 1983). Peterson and Krueger (1988) stated that in the present scenario, only aeroponics system is the most efficient plant cultivation system to grow the plant without the interference of soil comparing with other soilless techniques. The nutrient-mist system uses a minimum amount of water and provides an excellent environment for plant growth (Buer et al. 1996). Hessel et al. (1993) and Clawson et al. (2000) examined the usefulness of the aeroponics system for spaceflight and revealed that system contributes to advances in several areas of plant root studies. The studies include root micro-organisms (Hung and Sylvia 1988; Sylvia and Jarstfer 1992; Wagner and Wilkinson 1992) root response to drought (Hubick et al. 1982) effects of oxygen concentrations on root growth (Shrausberg and Rakitina 1970; Soffer and Burger 1988); legume-rhizobia interaction (Zobel et al. 1976); arbucular mycorrhizal fungi production (Sylvia and Hubbel 1986) and plant cultivar differences in root growth. The system achieved the performance for saving the water up to 99%, nutrients 50% and 45% less time than soil-based cultivation (NASA 2006). The adaptability of the system could help the researchers to make the application to spaceflight plant growth systems appealing. Zobel (1989) and Mirza et al. (1998) said in aeroponics system plant roots quickly nourish the available nutrients and grows under controlled conditions. The controlled conditions include uniform nutrients concentration, EC and pH values,
temperature, humidity, light intensity, atomization frequency, atomization spray time, atomization interval time, and oxygen availability. However, the plant grows speedily in the system due to the sterile environment and abundant oxygen availability in the growth chamber. However, several research studies practiced the modern plant growing technology for the cultivation of horticultural ornamental, the root of herbs and root based medicinal plants production (Clayton and Lamberton 1964; Cho et al. 1996; Park and Chiang 1997; Burgess et al. 1998; Garrido et al. 1998a; Garrido et al. 1998b; Scoggins and Mills 1998; Molitor et al. 1999; Kamies et al. 2010).

Stoner (1983) reported that before 1966s the aeroponics system was performed only as a laboratory analysis to investigate the plant root structure. However, in 1966, the system exits the laboratories to move into the field to cultivate the plants for commercial purposes. In 1982 the system got public attention when ‘The Land’ pavilion at Disney’s Epcot Center opened. Finally, in 1983 GTi successfully introduced the first commercial aeroponics system known as Genesis Rooting system, commonly called the Genesis Machine. The machine was operated and controlled with a different type of microchips and simply joined within an electrical outlet and a water atomizer nozzle. Whereas, NASA also took interest to push aeroponics for further studies and applied the technique to grow the plant in space. Several academics research studies concluded and evidenced to support the system and cultivated plant with significant yield. The researchers pointed out that the soil-less technique made the aeroponics cultivated crops easier for harvest (Cho et al. 1996; Park and Chiang 1997; Biddinger et al. 1998; Scoggins and Mills 1998). Hoffman and Kolb (1997) grew winter wheat seedlings in Aeroponics system and determined the effect of barley yellow dwarf on plant root and shoot. The results indicated that barley yellow dwarf severely reduced root length, distance from seminal root tip to the nearest lateral root, and the root to shoot ratio. In some cultivars, the shoot percent dry matter and number of adventitious roots were increased by barley yellow dwarf. A study conducted in 1991–92 in Sardinia, Italy, by growing certain hybrid tomato varieties. The result stated that certain hybrid tomato varieties produced abundant and excellent commercial quality fruit in a very short time (Leoni et al. 2008). In 2001, a University of Arizona study aimed to determine the effect of aeroponics on plants prized for the medicinal properties of their roots by growing echinacea and burdock. The researchers got some startling results. The echinacea plant suffered fungal and insect outbreaks and the yield was still comparable to those found in natural field condition. While the burdock greatly outperformed its outdoor counterparts: the harvested roots were highly yielded than those found in natural field conditions. Chang et al. (2012) said aeroponics could be an appropriate system for producing potato minitubers. He found that an interruption of nutrient supply at stolon growth stage significantly increases root activity, restricts stolon growth, and finally induces tuber initiation. Therefore, non-tuberizing conditions such as hot temperatures and late season cultivars favor the use of this nutrient interruption technique. He and Lee (1998) found that the growth of shoot, root and photosynthetic responses of three cultivars of Lettuce (Lactuca sativa L.) confined to different root zone temperatures and growth irradiances under tropical aerial conditions was better to the aeroponically grown crops compared to the control. Luo et al. (2009) developed a very successful method of producing hearted lettuce in the tropics using aeroponics and root cooling. It was also found that the effects of elevated root zone CO₂ and air temperature on photosynthetic gas exchange, nitrate uptake and total reduced nitrogen content in aeroponically grown lettuce plants (Johnstone et al. 2011). A comparison of the product yield, total phenolics, total flavonoids, and antioxidant properties was done in different leafy vegetables/herbs and fruit crops grown in aeroponics growing systems and in the field. The antioxidant properties of those crops were evaluated using 2,2-diphenyl-1-picrylhydrazyl (DDPH) and cellular antioxidant (CAA) assays. In general, the study shows that the plants grown in the aeroponics system had a higher yield and comparable phenolics, flavonoids, and antioxidant properties as compared to those grown in the soil (Chandra et al. 2014). The vitamin C content was highest in all herbs cultivated in aeroponics whereas the essential content oil was highest in Holy Basil and Perilla cultivated in the substrate (Bohme
In Aeroponics system, the seedlings of *Acacia mangium* were cultivated and result showed it is the well-known technique for furnishing a very rich air environment around the plant root, enhance the performance and induce rapid growth of seedlings under greenhouse conditions (Martin-Laurent et al. 2000). Thus, the aeroponics system has potential to increase income and reduce the cost of production of quality seed, thereby, making it more accessible to growers in developing countries.

The present study aims to describe a novel approach of plant cultivation under the soil-less system and provides the brief literature survey about the aeroponics system. We reviewed the literature survey and found that several research studies have been concluded and recommend that in future the world increasing food demands will highlight several challenges not only for human as well as for animals. Under such circumstances, the aeroponics system is considered as safe and environmentally friendly plant cultivation method. The system can conserve water and energy. It uses nutrient rich-water recirculation hence; system offers lower water and energy inputs per unit growing area (Ritter et al. 2001; Farran and Mingo-Castel 2006; Lester 2014) and offer a means of controlling the atmosphere in the root zone and provide a method for measuring of cell division and physiological responses of plant (Smucker and Erickson 1976). The adoption of the system would be economical, beneficial and valuable for local farmers to perform agricultural activities. It would be the best solution to provide the clean, fresh vegetable and sustenance to rapidly booming population.

**World interest towards aeroponics system**

Humans necessitate needs the fresh and clean food for survival. The fresh and clean food comes from many resources, one of them is a plant. However, the world population is rapidly growing and putting pressure on available natural resources to produce food. The increasing pressure is causing several serious problems such as global warming and reduction in natural resources. Pinstrup-Andersen (2017) reported that at the same time the water scarcity, drawdown of groundwater level, water mismanagement, waterlogging and salination of soils could effect on the food production and cause a severe problem in many countries. Besides, the researchers are conducting experimental studies to search out the alternative and appropriate technologies in agriculture. One aspect of their investigations is the plant, and their ability to survive and flourish under distinct situations. In fact, the soil, water, and surrounding environmental conditions are three essential factors to grow a healthy plant. NASA (2006) study reported that what happens if the soil

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*Figure 2. Aeroponics system. 1. Fog transmission pipeline; 2. Nutrient solution reflux line; 3. Tube-axial fan; 4. Atomizing chamber; 5. Ultrasonic atomizer; 6. Cultivation box; 7. Control line of Ultrasonic atomizer; 8. Batter board of ultrasonic atomizer.*

*Figure 3. Aeroponics and NASA (Hydroponics gardening 2014).*
is completely taken out of the equation still plant will grow. Their study concluded that yes plant could grow under such condition by providing nutrient spray mist in the air as shown in Figure 3. The High-performance crop production technology is rapidly gaining the intention of the people as a modern-day agriculture activity. Nowadays, it has been significantly used in agriculture around the world (Hoehn 1998). While Decade ago, the utilization of the system was limited almost around the world aspect some countries like China and Korea. They used an aeroponics system for commercial application to produce good qualities of potato seeds (Kim et al. 1999). The use of aeroponics for plant cultivation is very recent in Europe. Currently, it is practiced in South America (Mateus-Rodríguez et al. 2013), and the attempts have been made to present the system in African countries (Otazú 2014). The system is highly accepted and recommended for plant cultivation in following countries include: Taiwan (Wu et al. 1997); Australia, (Mohammad et al. 2000); Singapore (Wilson 2000); France (Souret and Weathers 2000); Spain (Ritter et al. 2001); Thailand (Sriha-jong et al. 2006); New Zealand (Johnstone et al. 2011); Japan (Kitya et al. 2008); Russia (Akopyan et al. 2009); Malaysia (Tik et al. 2009); Germany (Germer et al. 2011); South Korea (Chang et al. 2012); India (Buckseth et al. 2016); Indonesia (Idris and Sani 2012); Bolivia, Colombia, Ecuador, Ethiopia, Mongolia, Peru and Uzbekistan (CIP 2012); Sri Lanka (Weerahewa 2013); Italy (Nijis 2013); Kenya (Mbiyu et al. 2012); Korea (Yeo et al. 2013); African countries like Uganda, Tanzania, Mozambique, Malawi, Ghana, Ethiopia (Niyi 2013; Kumari et al. 2016); Tennesse et al. 2017; Oteng-Darko et al. 2017); Slovakia (Pal et al. 2014); Vietnam (ICAA 2014); Bhutan (Wangchuk 2014); Canada (Oraby et al. 2015); Greece (Salachas et al. 2015); Nigeria (Ogbole 2016); Philippine (Philippines 2016) Iran (Shabiani et al. 2013); Poland (Rykaczewska 2016); Egypt (Singer et al. 2012) and Abu Dhabi (Alshrouf 2017).

Components and atomizers required for aeroponics system

Spray misters and droplet size

Aeroponics is a modern-day plant growing technique in the agriculture. It does not require any single soil particle to provide essential nutrient for plant growth. However, in aeroponics plant roots receive nutrient spray mist eject from the atomization nozzles. The atomization is the method of breaking up liquid molecules into fine droplets (Avvaru et al. 2006). US Patent Publication No 2011/0023359 A1 described that the most common aeroponics system uses pressurized water that is sprayed onto the roots using simple garden sprinkler-type fluid nozzles. However, different atomizers are developed in several disciplines along with different spray patterns and orifices to provide tiny liquid droplets down to 1 micron. The atomizers are categorized as high, medium and low-frequency atomization as shown in Figure 4 (Rajan and Pandit 2001; Lu et al. 2009). The atomization nozzles with small orifices could create the problems such as nozzle clogging and cause to stop the water nutrient supply. In order, to avoid the nozzle orifice clogging the mesh filters are used to prevent the nozzle clogging. While the larger nozzles with bigger orifice decrease the chances of nozzle blockage but require high-pressure to operate. It is essential to select the suitable atomization nozzles to produce required droplet size. The droplet size varied from sub-microns to thousands of microns and characterized in a different classification. For high-pressure atomization nozzles, the droplet size is classified fine atomization mist of 10 to 100 microns. The jet spray nozzles with 0.000635 m (0.025-inch) and 0.0004064 m (0.016-inch) orifice under the operating pressure pump at 551580.5832 and 689475.729 Pa (80 to 100 psi) deliver the drop size of 5–50 microns and 5–25 microns respectively. However, in the aeroponics system, the ideal droplet size range for most of the plant species is in-between 30 and 100 microns. Within this range the smaller droplets saturate the air, maintaining humidity levels within the growth chamber. The conventional wisdom is that droplets below 30 microns tend to remain in the air like a fog and fail to achieve continuous plant growth. While droplets size more than 100 microns tend to fall out of the air before containing on the plant root, and too large droplet means less oxygen is present in the growth chamber. Selection of atomization nozzles should be based on the requirements of the growers. Ultrasonic foggers, whose working frequencies are between 1 and 3 MHz, are expensive and difficult to maintain. The foggers require special electrical circuits to drive them, so their structures are very complex. Also, they affect the chemical properties of the nutrient solution. The foggers are suitable for indoor gardening. The low-pressure nozzles are more convenient to use than foggers. These nozzles are cheap and easy to maintain, but their atomization quantities are small. Low pressure atomization nozzles are recommended for the small-scale gardening. The high-pressure atomization nozzles are operated with air-compressor. The compacted air delivers energy to break down liquid into very fine droplets. These nozzles have large atomization quantity, but the noises produced by them are very high. This type of atomization nozzles are recommended for large scale gardening.

Ultrasonic atomization fogger

The ultrasonic foggers are used to mimic ideal artificial humidity in the air with a little mist found rainforests. The atomization foggers are low-cost and resulted in high yield for plant development. It is a relatively small metallic covered device which comprises a plastic shell, built-in AC/DC adapter, and a small piezoelectric ultrasonic transducer. The piezoelectric transducer is the core component which generates the high-energy vibrations at frequencies from 0.5 to 3.0 MHz. The atomization foggers are placed in the center of the container under one to four inches of liquid solution. The foggers produce a very light solution spray that floats around the container in the air and sprays as thick fog like clouds. The fogger generates a fine mist having a particle diameter of only a few microns (http://www.farnell.com/datasheets/81205.pdf). These fine particles are cable of carrying nutrients from the standing water nutrient from the reservoir towards the plant root. Benefits include humidification and exponentially improved root exposure to oxygen. These improve oxygen flow to the roots while creating a suitable humid atmosphere for the plant to thrive in and for successful growth (https://en.wikipedia.org/wiki/Ultrasound_hydroponic_fogger). The fog is cold and slightly wet but possesses no threat to the user (http://www.tech-faq.
Although, the horticulturalists might be purchase commercial ultrasonic foggers for plant cultivation and to layout the indoor garden with a small ultrasonic fogger as shown in Figure 5.

**Pressure (Airless and Air spray) atomization nozzles**

The report was published (www.pnramerica.com/pdfs/p49_53.pdf) on Air-atomization nozzles express that several industrial practices are implementing nozzles to atomize the liquids into the fine particle. However, the standard atomization nozzles are used to atomize the liquid from the small orifice with low and high-pressure to get the fine particles. Pressure atomization is a method to create a fine spray and that uses air to atomize the liquid. In most instances when small droplets are required, the air-atomization nozzles are operated by providing the air with high-pressure through the air-compressed container. The compacted air delivers energy to break down the larger liquid particles into very fine particles. The liquid is distributed through the orifice into the atomization nozzle, where high-pressure air stream produces the shearing force to break up the large liquid molecules. The air stream carrying the fine particle collides with resonator located in front of the nozzle and generates a field of high-frequency ultrasonic sound waves. Their exposure causes the larger droplets to break up into a fine mist spray. The droplet size dependent on the operating frequency. The audible noise produced by high-pressure nozzles is extremely high. The nozzle structure is designed as an internal mix or external mix set-up. The pressure atomization is a method of fine spray application that does not use compressed air to atomize the liquid. The discharge of the nozzle depends on the liquid flow, size of the spray head and pressure pump. However, the atomization nozzles are placed in the center of the growth chamber and connected with pressure pump to provide water nutrient mist. While the roots are suspended above or inside the chamber and directly precipitate

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**Figure 4.** Atomization nozzles used in aeroponics system: (a) Ultrasonic atomization fogger; (b) High-pressure (Air) atomization nozzle; (c) Pressure (airless) atomization nozzle.

**Figure 5.** Lettuce cultivated in aeroponics ultrasonic atomization fogger system: (a) Plant leaves; (b) Plant root.
with uniform water nutrient mist. The aeroponics system designed with pressure nozzle is more convenient, simple to operate and maintain. The main advantage of the quick adoption of this system is the low operational cost. Figure 6 shows the lettuce plant cultivated in an aeroponics system with air and airless atomization nozzle.

**pH and EC (electrical conductivity) meter**

The pH is defined as measure the degree of acidity or alkalinity of a liquid solution. Although, the EC is a measure of all of the salts dissolved in water, including those added to the fertilizer. The unit of EC is ds m\(^{-1}\). Different methods are used to determine the pH and EC value of the nutrient solution. However, the most common, simple and easy way to measure the value is pH and EC meter. In the aeroponics system, where water and nutrient solution is recycled repeatedly. Therefore, it is important to regularly measure the pH and EC value of the nutrient solution for successful plant growth. If the readings are not at the proper level, the grower needs to adjust them. The ideal pH and EC range for each plant depend on available environmental conditions (Sonneveld and Voogt 2009). Although, the pH and EC values of the prepared nutrient solution could not exceed than 7 and 2.5ds m\(^{-1}\). The optimum EC and pH values of nutrient solution in aeroponics system lie between 1.5 to 2.5 ds m\(^{-1}\) and 5.5 to 6.5 and 5.0 as shown in Table 1 (Resh 2004; Chadirin et al. 2007).

**Humidity and dissolved oxygen concentration**

Aeroponics system is the application of plant growth without soil by delivering water nutrient solution in the air. The system is based on 100% available moisture in the growth chamber. In addition, the humidity is the amount of available water in the growth chamber as water vapor content. In the aeroponics system, humidity is the main component required for successful plant growth and development. However, the plant growth is significantly affected by increase and decrease in relative humidity (Ford and Thorne 1974; Schussler 1992). It effects on plant physiological functions and creates diseases problems (Gislerod and Mortensen 1990). Therefore, it is important to regularly maintain and control the required humidity concentration of growth chamber based on plant need. The aeroponics system provides best oxygenation environment for plant growth. It allows plant roots to grow in the air with a plentiful supply of oxygen. Hence, no any additional mechanism is required.

**Light and temperature**

Temperature is the primary environmental factor that influences the frequency of plant growth and development. It influences not only on the initial growing stage but also on harvesting period (Hatfield and Prueger 2015). In the aeroponics system, both air and nutrient solution temperature should be controlled for quick plant maturation. As temperatures rise, the chemical processes proceed at faster rates and deteriorate the enzyme activities. The optimum temperature range for all plants is 15–25°C. However, the temperature there is no any medium to support the plant. Many studies conducted without soil. Therefore, it is essential for the grower to fix the atomization spray time and interval time based on the plant requirement. The wrong schedule could create serious problems for plant growth because in the system there is no any medium to support the plant. Many research studies had been successfully cultivated plant under different atomization spray time and interval time. However, the potato had been cultivated under the atomization spray time and interval time 20-sec on and 5-min off, 3-min on and 5-min off, 3-sec on and 10-min off, 30-sec on and 5-min off, 10-sec on and 20-mint off, 15-min on and 15-min off during day time and 15-min on and 1-h off during night time, and 10-sec on and 3-min off during day time and 10-sec on 5-min off during night time, respectively (Farran and Mingo-Castal 2006; Ritter et al. 2001; Abdullaeteef et al. 2012; Chang et al. 2012; Mateus-Rodriguez et al. 2012; Tsoka et al. 2012; Rykaczewska 2016). Biddinger et al. (1998) and Osvald et al. (2001) successfully cultivated the tomato under the atomization spray time and interval time of 3-sec on and 10-min off, and 60-sec on and 5-min off respectively. Moreover, many studies cultivated several plants under different atomization spray time and interval time such as cucumber 7-sec on and 10-min off (Peterson and Krueger 1988); lettuce 1.5-min on and 5-min off (Lactuca sativa L.) (Kacjan-Marsic and Osvald 2002); Saffron (Crocus sativus L.) 1-min on and 1-min off (Souret and Weathers 2000); 96 Echinacea (Echinacea purpurea) and 30 burdocks (Arctium lappa) 30-sec on and 60-sec off (Pagiariulo and Hayden 2000); Anthurium andraeanum 15-sec on and 15 mints off (Fascella and Zizzo 2007); Acacia

**Table 1.** Represents the recommended pH and EC value for some plants (Kim et al. 1999; Farran and Mingo-Castal 2006; Abdullaheteef et al. 2012; Irman and Ikhsan 2012).

| Plant          | pH  | EC  |
|---------------|-----|-----|
| Onions        | 6.0–7.0 | 1.4–1.8 |
| Cucumber      | 5.8–6.0 | 1.7–2.2 |
| Carrots       | 5.8–6.4 | 1.6–2.0 |
| Spanish       | 5.5–5.6 | 1.8–2.3 |
| Lettuce       | 5.5–6.5 | 0.8–1.2 |
| Tomato        | 5.5–6.5 | 2.0–5.0 |
| Potato        | 5.0–6.0 | 2.0–2.5 |

Misting frequency and nutrient reservoir

In the aeroponics system, the atomization spray time and interval time are the essential factors for successful plant cultivation. As we discussed, the aeroponics system is performed without soil. Therefore, it is essential for the grower to fix the atomization spray time and interval time based on the plant requirement. The wrong schedule could create serious problems for plant growth because in the system there is no any medium to support the plant. Many research studies had been successfully cultivated plant under different atomization spray time and interval time. However, the potato had been cultivated under the atomization spray time and interval time 20-sec on and 5-min off, 3-min on and 5-min off, 3-sec on and 10-min off, 30-sec on and 5-min off, 10-sec on and 20-min off, 15-min on and 15-min off during day time and 15-min on and 1-h off during night time, and 10-sec on and 3-min off during day time and 10-sec on 5-min off during night time, respectively (Farran and Mingo-Castal 2006; Ritter et al. 2001; Abdullateef et al. 2012; Chang et al. 2012; Mateus-Rodriguez et al. 2012; Tsoka et al. 2012; Rykaczewska 2016). Biddinger et al. (1998) and Osvald et al. (2001) successfully cultivated the tomato under the atomization spray time and interval time of 3-sec on and 10-min off, and 60-sec on and 5-min off respectively. Moreover, many studies cultivated several plants under different atomization spray time and interval time such as cucumber 7-sec on and 10-min off (Peterson and Krueger 1988); lettuce1.5-min on and 5-min off (Lactuca sativa L.) (Kacjan-Marsic and Osvald 2002); Saffron (Crocos sativus L.) 1-min on and 1-min off (Souret and Weathers 2000); 96 Echinacea (Echinacea purpurea) and 30 burdocks (Arctium lappa) 30-sec on and 60-sec off (Pagiariulo and Hayden 2000); Anthurium andraeanum 15-sec on and 15 mints off (Fascella and Zizzo 2007); Acacia
Mangium 40-sec on and 30-sec off (Weber et al. 2007); Maize 1-sec on and 15-mins off (du Toit et al. 1997); Acacia mangium 15-sec on and 1-min off (Martin-Laurent et al. 1997); Peas (*Pisum sativum*) 3-sec on and 10-mins off (Rao et al. 1995) Onion 7-sec on and 90-sec off (Jarstfer et al. 1998) and Whitei (*Hook. F*), Skeels, T. riparia (Hochst.) Codd and C. speciosa (l.f) Hassk 2-sec on and 2-min off (Kumari et al. 2016). In the aeroponics system, the nutrient reservoir is designated as separate or outside and inside or within the growth chamber. The purpose of the nutrient reservoir is to store the solution. In the separate or outside reservoir, the atomization nozzles are connected to the delivery line through pressure pump to supply the solution to the growth chamber. The drain line is provided in the growth chamber to recycle excess solution. Although, in inside reservoir, the atomization nozzles directly get the nutrient supply from the bottom of the growth chamber, where it drips back down after misting on the root system.

**Role of computer intelligent control techniques in aeroponics system**

At present time-controlled environment agriculture demands extra efficiency for substantial returns. Humans also need decision making and automatic sophisticated computer monitoring and control technique to reduce intentions and enhance the efficiency of the system (Tik et al. 2009). Akyildiz et al. (2002) surveyed to adopt different computer intelligent and advanced wireless network techniques in various fields. He and coworkers reported that currently, agriculture is a potential field of deployment with computer networking techniques. The efficiency of the agriculture activities in a controlled environment could be enhanced by adopting the computer intelligent techniques. Tik et al. (2009) reported that WSN in agriculture is mainly focused on two major areas: (i) experimental or simulation work on various routing protocols and network topologies to increase data transfer rates whilst maintaining or reducing power consumption (Galmes 2006; Camilli and Cugnasca 2007; Konstantinos et al. 2007) and (ii) proof-of-concept applications to demonstrate the efficiency and efficacy of using sensor (Figure 7) networks to monitor and control agriculture management strategies (Dinh et al. 2007; Narasimhan et al. 2007; Pierce and Elliott 2008). However, the aeroponics system is the science of plant cultivation by controlling the surrounding environmental conditions without soil. Therefore, there is a
maximum possibility to face many problems and challenges associated with plant growth. The problems and challenges include a water nutrient buffer solution, failure of the delivery pump, spray time, time interval, and atomizer frequency. Moreover, the environmental problems include root temperature, humidity percentage, and light intensity. These problems require special care to escape damage or speedy death of plants during cultivation period. Hence, it is important for growers to control and maintain them on proper time as exposed. There are different ways to deal with these challenges by accepting the modern techniques. Different research studies recommended that these problems could be monitored by adopting the automatic artificial intelligence techniques in the aeroponics system.

Pala et al. (2014) worked on fault detecting by applying computer programming methods (Figure 8) in the aeroponics system. He and team concluded that the Neural-network system is the efficient technique of detecting mechanical and biological faults in the deep trough from the system. The detected defects are based on two separate fault conditions. The first condition represents the fault detection information in the system on behalf of working sensors: (water nutrient solution; EC and pH value, humidity, air temperature and light intensity). The second fault detection is based on the biological faults occurring in the system (transpiration rate) (Ferentinos et al. 2003a; Ferentinos and Albright 2003b). The obtained real-time data from the system could apply to maintain the growth chamber temperature, ventilation from growth chamber, light intensity, and available water nutrients solutions properties (Tik et al. 2009; Sahu and Mazumdar 2012; Song et al. 2012).

Mechanization and optimizing of root environment in aeroponics cultivation system
Throughout history and literature review, man has endeavored to understand and manipulate his surrounding environment. One aspect of his investigation was the plant, and their ability to survive and flourish under distinct situations. The research results indicated that direct and adequate supply of mineral nutrients is a significant factor in the creation of the root domain environment. Hayden (2006) reported that plant root development and growth laid on several factors include the initiation, elongation, and spreading out of fresh root axes. Plant root structure responds to the root zone environment by substituting in growth and branching systems as well the variations in plant hormone synthesis and response probably mediate these plastic responses to the root zone environment as well as contribute to genetic variances in root architecture and plasticity. Jonathan et al. (2012) revealed that plant root growth and development depends on an adequate quantity of carbohydrates supply from surrounding photosynthesis concentration and available environmental conditions. Therefore, many roots surrounding environmental conditions that influence photosynthesis, including water availability, light intensity, temperature, and nutrient availability may impact on root growth by affecting carbohydrate supply to the plant roots (Kawasaki et al. 2014). Compared with the other traditional cultivation methods, aerosol culture becomes the advantages of free extension of the root system, (Vincenzoni 1977; Sumarni et al. 2013) direct and sufficient oxygen uptake, rapid and convenient water absorption, and full mineralization with mist supply, creating the best root environment for plant growth.

Aeroponics is defined as a system of soil-less culture where roots are continuously or discontinuously bathed with fine drops of nutrient-rich water. The method requires no any substrate like rock wool, dirt, coir, vermiculite or perlite and entails growing plants with their roots periodically wetted with a fine mist of atomized nutrients. Excellent aeration is the main advantage of aeroponics (Carter 1942). Plant root structure response to the root zone environment via substituting in growth and branching systems. Thus, only aeroponics provides numerous advantages include a free extension of the root system, direct and sufficient oxygen uptake, rapid and provision of uniform nutrient spray mist with best root growth environment (Vincenzoni 1977; Sumarni et al. 2013).

Plant growing system
As discussed above, the aeroponics system differs from both Hydroponic and in vitro plant growing techniques. Unlike hydroponic system, which uses water nutrient-rich solution as a growing medium and provides essential nutrient for sustain plant growth. However, it is conducted without any growing medium (Lakkireddy et al. 2012). In the system, the nursery plants might be either raised as seedlings using specially designed lattice pots or cuttings could be placed directly into the system for rapid root formation. Lattice pots allow the root system to develop down into the growth chamber where it is regularly misted with nutrient under controlled conditions. Zobel et al. (1976) reported that root zone environmental conditions play a significant role in healthy plant growth and retaining the excellent quality of seed production. Siddique et al. (2015) revealed that only efficient root system provides unobstructed growth space for the plant under atomization conditions. Soffer and Burger (1988) reported that once plant located in the atomization system roots start to get most favorable root aeration system. The lower portion of the plant entirely suspends in the mist air environment and provide root organism to gain the required factors. The base of the cutting is supplied with high levels of oxygen and moisture in a humid environment and helps the plant to get 100% of the fresh oxygen from the air to promote and support root metabolism and accelerates formation. The increasing metabolism rate of plant growth was reported up to 10 times greater than soil system (Stoner 1983; Chiapanthenga et al. 2012).

Nutrient solution management in aeroponics system
Aeroponics uses less water and nutrients because the plant roots are sprayed at intervals using a precise droplet size that could utilize most efficiently by osmosis to nourish the plant. The nutrient solution is an aqueous solution mainly containing soluble salts of necessary components for higher plant yield (Steiner 1968). The essential inorganics ions have important and clear physiological role and their absence prevents the plant life growth stage (Taiz and Zeiger 1998). However, the nutrient composition depends on the plant cultivation method, the kind of medium, growth stage, weather, method of applying nutrient solution, etc (Guang-jae et al. 2007). The plants need 17 essential inorganics nutrient for maintaining optimum health and significant yield (Kochian 2000; Bailey and Nelson 2012). Rolot et al. (2002) reported...
the main necessary nutrient components required for vigorous plant growth included phosphorus (P), sulfur (S), potassium (K), nitrogen (N), and zinc (Zn). The carbon (C) and oxygen (O) is directly supplied from the atmosphere. The plant cannot exist without the deficiency of these elements, and these elements cannot be exchanged with any other nutrients. Therefore, in the aeroponics system, the plant is grown without soil by providing nutrient mist through atomization nozzles. It is important to supply accurate essential nutrient on proper time with required concentration. Up to now, different researchers used different nutrients concentration for preparing the nutrient-rich water. Dennis, Hoagland, and Daniel recognized several recipes for preparing the mineral nutrient solution for water culture. Knop and other plant physiologists revealed that K, Mg, Ca, Fe, and P along with S, C, N, H, and O are all essential nutrient elements for plant life (Lakkireddy et al. 2012). There are several nutrient solutions recipes and Table 2 shows some of them. These recipes are mostly used in the aeroponics system until now. The success or failure of the system primarily depends on the strict nutrient management. Therefore, it is important to manipulate and adjust the EC and pH level of water nutrient solution. Moreover, replace the nutrient solution after every 2 to 3 days or whenever necessary.

### Aeroponics engineering and potential challenges

The aeroponics system is the modern technique of the plant cultivation. Until now, it is not entirely implemented around the world. The system has many potential challenges which could be answered through research studies. Buckseth et al. (2016) and Stoner and Clawson (1998) revealed that in the aeroponics system the main problem is related to water nutrient droplet size. The larger droplets permit the less supply of the oxygen availability in the root zone. The smaller droplets produce too much root hair without developing a lateral root system for sustainable growth. Currently, most of the studies on the aeroponics system are based on the growth, yield, and quality of the plant. However, only limited studies had been carried out to determine the influence of various droplet sizes on plant yield and nutrient physio-chemical properties of the nutrient solution. The main potential challenge and drawback of the system is constant power supply throughout the plant growth. Any prolonged rupture of power energy shut down the nutrient supply and contributes to permanent plant damage. The mineralization of the ultrasonic transducers requires attention and may be prone to potential components failure.

| Nutrient | Steiner (1984) | Cooper (1988) | Hewitt (1966) | Hoagland and Arnon (1938) |
|----------|---------------|---------------|---------------|--------------------------|
| N        | 168           | 200–236       | 168           | 210                      |
| P        | 31            | 60            | 61            | 31                       |
| K        | 273           | 300           | 156           | 234                      |
| Ca       | 180           | 170–185       | 150           | 160                      |
| Mg       | 48            | 50            | 36            | 34                       |
| S        | 336           | 68            | 48            | 64                       |
| Fe       | 2–4           | 12            | 2.8           | 2.5                      |
| Cu       | 0.02          | 0.1           | 0.064         | 0.02                     |
| Zn       | 0.11          | 0.1           | 0.065         | 0.05                     |
| Mn       | 0.62          | 2.0           | 0.54          | 0.5                      |
| B        | 0.44          | 0.3           | 0.54          | 0.5                      |
| Mo       | Not considered| 0.2           | 0.04          | 0.01                     |

**Figure 8.** The proposed architecture of control and communication mechanism between human operator and Aeroponics system (Pala et al. 2014).
Advantages of aeroponics system

Martin-Laurent et al. (1999) suggested that Aeroponics technique is a current innovative and appropriate technology. It has the potential to cultivate plants in large quantities, tree saplings associated with soil micro-organisms, such as AM fungi, for reforestation of degraded land in the humid regions. Aeroponics is an indoor horticulture practice. It is the best to adopt aeroponics in areas where the soil is not suitable for plant growth. Aeroponics is an incredible amount of water as little as compared with other plant growing systems. The system reduces the labor cost, consumes less water usage by 98%, fertilizer usage by 60%, pesticide and herbicides usage by 100% and maximize plant yield by 45% to 75% than either hydroponics or geoponics system (Stoner 1983; NASA 2006). The nutrient solution could be recycled easily for reuse. The system allows for vertical farming, thus increasing the yield by more space for the plant. The possibilities of multiple harvests of a single perennial crop and accelerated cultivation cycle due to the increased rate of growth and maturation. The mature plant could be removed easily at any time without disturbance another plant. The diseases could not expand quickly because of clean root material free from soil, soil-borne organisms and adulteration from foreign plant species contaminants. While in other soil-less system plant diseases could spread through nutrient distribution in growth chamber from plant to plant. The plant receives 100% of the available carbon dioxide and oxygen to the leaves, stems, roots, and accelerating growth with reducing rooting time. The system is not subjected to weather conditions. The plants could be grown and harvest throughout the year without any interference of soil, pesticides, and residue. It is environmentally friendly and economically efficient plant growing system.

Disadvantages of aeroponics system

- Expensive for long scale production
- The plant grower must need a specific level of proficiency to operate the system.
- The grower must have the information about the appropriate quantity of required nutrient for plant growth in the system.
- It is important to supply the required concentration of the nutrients. There is no any solid culture to absorb the excess nutrients if supply excess plant will die.
- The system design material is little expensive. As the well-designed system requires advanced equipment. It mainly constant high-pressure pumps, atomization nozzles, EC, and pH measuring devices, temperature, light intensity and humidity sensors and timer to control the system.

What we know and what remains to be known in aeroponics system

Presently, aeroponics cultivation is implicated for growing vegetable crops. It is a relatively new technology. Therefore, enough material about the system is yet distant. Otazú (2014) declared that in aeroponics system production is essentially sensitive to climate and the vegetative period increase by 1–2 months. It can substantially increase income and decrease the seed production cost which represents the system as more convenient to growers. The sequential plant harvesting is required, and the initial cost could be obtained quickly. The system must analyze with new cultivars and the artificial conditions including extra lights, temperature and humidity control system. The artificial conditions should be equipped in the greenhouse for the plant cultivation at different latitudes. The study of root temperature is not as well documented. The interrelationships among root and shoot temperature influence on growth are still unidentified. The evaluation, assessment, and utilization of aeroponics system for commercial plant developing purpose are not studied. However, most of the studies are focused on root research, as root microorganisms and root responses to drought. Each plant needs a specific optimum supply of the nutrient solution at specific growth point. So, the optimum concentration of nutrient solution for each plant should be investigated and distinguished. The plant spacing should be figured out for each cultivar. Different plant materials such as cuttings and tuber sprouts should be compared in the system. In the aeroponics system, the traditional methods of pest/disease control are not applicable thus the modern diseases control should be developed. Based on weather and field production conditions, the best plant production period should be determined for each plant. The artificial lighting could be used to grow the plant.

Future application prospects

Previous research works done on the aeroponics system are in favor to adopt this cultivation system. In a relatively short period, the aeroponics system has adopted in many situations from outdoor field culture to indoor greenhouse culture. It is also recommended as a highly specialized culture in the space application and space-age technique. At the same time, the system could be used in developing countries of the Third World to accommodate intensive food production in the limited area. In future, aeroponics would effectively use in those regions where fresh water and fertile soils will not be accessible. Thus, it could be the potential application for food production in those regions having vast parts of the nonarable land, small area and big population, and as well in desert regions. The system could be highly practiced to grow vegetables in small countries whose chief industry is tourism. The tourist facilities restaurants and hotels might grow their own fresh vegetables and provide fresh food to the tourist.

Conclusion

This review paper of the existing literature revealed as the population increases. The demands for clean and fresh food increases alarmingly with the population. People will turn to new plant growing technologies to fill up increasing food demands. Moreover, this review article concluded that aeroponics is the modern, innovative and informative technology for plant cultivation without corporation of the soil. The system is the best plant growing technology in many aspects comparing with different cultivation system. The system is quickly increasing momentum, popularity and fastest growing sector of modern agriculture. It would be effectively employed in various countries for vegetable production where natural resources are insufficient.
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